

ImmoGap – Analysis of the performance gap of apartment buildings

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Abstract. Within the project ImmoGap, the so-called performance gap for multifamily buildings was analysed. It contributes to a better classification and a clearer definition of the term "performance gap". As a first step, a literature study on this topic was carried out. In principle, the "Performance Gap" is understood as an additional consumption of energy or a failure to meet energy benchmarks. The term "Performance Gap" suggests that a desired service is not provided. This is critical, because there are several reasons why a building consumes more energy than originally planned. In the project, the heating energy consumption of 65 multifamily buildings was compared with the design heating demand according to the Swiss standard SIA 380/1 (based on EN ISO 13790:2008). In contrast to other studies, the project team was able to access measurement data with a very high time resolution. On average, the heat demand calculated with standard use is exceeded by 44%. Four of the buildings show an additional consumption between 100% and 115%. Detailed investigations with simulations and measurements show that the additional consumption can largely be explained by the user behaviour regarding shading, ventilation and room temperature, which deviate from the standard. If the observed user behaviour was already used in the demand calculation, the examined buildings on average would not show any "performance gap".

1 Introduction

In Switzerland, around 1.6 million buildings account for about half of the country's primary energy demand [1]. For this reason, the building sector plays an important role in energy research and, in particular, in increasing the efficiency. A similar situation can be found in different European countries [2]. Various studies have shown that there is sometimes a clear difference between the energy consumption according to the design calculations and the real consumption of buildings measured during operation. This is referred to as the "performance gap". The present study with the acronym "ImmoGap" investigates causes of the performance gap. The study focuses on the evaluation of multi-family houses (MFH), as they are expected to offer the greatest potential for reducing energy consumption [3].

In a first step, a literature study was carried out in order to focus the research on the most essential factors regarding the performance gap. In a second step, 65 apartment buildings were investigated with regard to their space heating consumption. In the end, individual findings from the measurement data evaluation were examined in more detail using dynamic annual building simulations.

2 Literature review

2.1 General

In the literature, the so-called performance gap in the building sector describes the difference in energy consumption between planning and as-built operation. The performance gap is also occasionally referred to as rebound and prebound effects [4,5]. A rebound effect is when increases in efficiency are compensated by increased consumption or changed user behaviour that are themselves a consequence of the efficiency measures. This can be seen, for example, in the increased demands placed on room temperature over the past decades [6,7]. The prebound effect describes in the building sector the under-consumption of energy between standard or design calculation and the measured consumption. Especially in older buildings, this performance gap with a negative prefix can be found. From the authors' point of view, the rebound and prebound effect is a part or a cause of the performance gap and therefore not to be equated with the performance gap.

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2.2 Reduced consumption for old buildings

Various studies [7–11] show that in older, unrenovated buildings up to the year of construction 1995 and with a design heating demand of more than 100-130 kWh/m²a, the energy consumption is usually lower than the calculated energy demand. The overestimation of the energy demand can be significant with 35% to 200%. On the one hand, this is pleasant because less energy is consumed than assumed. For the building owners, however, this means that the effective reduction potential of renovations is significantly lower than the calculated potential, which has a negative impact on the profitability of energy-saving renovations. Furthermore, this circumstance suggests that the political reduction targets with regard to CO₂ emissions are unrealistically high with the targeted renovation paths and therefore may not be achieved [4].

The following reasons were found in literature for the reduced energy consumption for unrenovated old buildings:

- Lower room temperature than the assumed standard internal temperature (economical occupants) [4,6,12]
- Significantly lower air exchange rates compared to calculation according to the standards [4]
- Inhomogeneous heating: not all rooms are heated or have the same room air temperature setting [7,13].
- U-values are lower than assumed [11,13]
- Wind speeds assumed to be too high (resulting in significantly excessive heat transfer coefficients in the absence of insulation) [13]

A further cause not described in the examined literature, however, is the calculation methods that have changed over the years. These have been optimized and further developed over the years.

2.2 Increased energy consumption in new buildings or renovated buildings

A different picture can be seen for new buildings and renovations from about 2002 onwards with a design heating demand of less than 100 kWh/m²a. Passive and low-energy houses in particular often show significantly higher energy consumption than calculated [3,5,8,13–15]. A study of the heat and water cost accounting of 121 apartment buildings in Switzerland showed that one third of new apartment buildings have up to 40% higher heating energy consumption and a further third consume up to 100% more than expected according to the energy standard calculation [15]. The deviations are very different depending on the heating system. This excessive consumption of the multi-family buildings is confirmed by further studies [3,16]. The following reasons can be found in the literature for the increased heating consumption:

- Room temperatures are higher than those specified in the standard [3,5–8,11,16–19]
- Overestimated boiler efficiency [3,5,10,18,20,21]

- Lower occupancy and thus smaller personal heat gain [5,8,17]
- Window ventilation in winter despite or in addition to mechanical ventilation [14,18]
- Insufficient air tightness values [17,18]
- Losses due to thermal bridges [5,18]
- Higher hot water consumption per capita [8]
- Missing hydraulic flow balancing [10]
- “Bio-Feedback”: Window ventilation due to short-term overheating situations [19]
- Functional and setting problems with the heating and hot water systems [3]

Insights into the performance gap could influence the controversial discussion in the construction industry about the insulation standard aimed for in future buildings. The question arises as to whether as much as possible should be invested in the building envelope or whether higher consumption should be tolerated if it is covered by renewable energy sources and efficient HVAC systems. In the case of new buildings, some German building experts [7] even assume that the heating demand of around 50 kWh/m²a will remain the standard. The reason for this is the individual user behaviour, which can only be influenced to a limited extent through sensitisation measures, so that there will always be a performance gap between design calculations and measurements.

The literature research confirms the importance of the study on user behaviour. Gill et al. [22] and Majcen [23] assume that a share of 50% of the additional consumption of energy can be attributed to the deviating user behaviour.

3 Methodology

3.1 The investigated building pool

Thanks to the cooperation with different energy contracting companies, it was possible to analyze the heat consumption of 65 apartment buildings. 78% of the evaluated building pool consists of buildings certified according to “Minergie”, a Swiss building label. In this study no comparison was made between the Swiss standard MuKEn [24] and the “Minergie” labeled buildings, as this was not the main focus of this work on the one hand, and no relevance is expected for understanding the deviation on the other. The properties were built between 2006 and 2014. Some key figures of the investigated buildings are shown in Table 1.

Depending on the year of construction, the edition of the Swiss standard (SIA 380/1 [25] which bases on the EN ISO 13790:2008 [26]) used to calculate the data needed for the energy certificate also varies accordingly. 23% of the building pool was calculated with the 2001 edition, 31% with the 2007 edition and 46% with the 2009 edition. The project also took into account that the 2009 edition refers to a different reference climate than the 2001 and 2007 editions. This has a direct impact on the weather correction of the measurement data (adjustment for heating degree-days).

As reference climate the weather station used for the energy certificate calculation (SIA 380/1) was used. Values that are not measured directly on site, such as global radiation and sunshine duration, were obtained from the corresponding climate stations of MeteoSwiss [27] for the required monitoring periods.

Although the outside temperature was measured on site for the control of the heating system, it was not used for the analysis. The reason was that for some buildings the deviations between the climate station and the on site measurement were too large. A cause for this can be, for example, direct solar radiation on the sensor.

Table 1. Selected key figures of the investigated building pool.

Figure	Min	Max	Mean
Standard Heating Demand [kWh/m ² a]	15.2	49.5	33.8
Reference Energy Area [m ²]	581	4610	1398
Apartments	5	23	8
Floors	3	7	4.7
Window Ratio [%]	11	39	23
Shape Factor (see Eq. 3)	0.8	1.6	1.3

3.2 Useful energy vs. final energy

In many studies on the performance gap, it is not clear whether the studies refer to the final energy or to the useful energy. Therefore, some of the results are not comparable between the studies. The final energy, which is usually easier to measure, is more often used for the analysis. The final energy is the consumption of natural gas, heating oil or electricity of the heating system. In contrast, useful energy is often not measured in a reasonably high time resolution. Nevertheless, statements are made about the performance gap with regard to the heating demand (useful energy) according to the standard calculations. This is problematic, as the efficiency of the heating system, that converts final energy to useful energy, can often only be estimated. This can strongly influence the results. In this study, all analysis were made at the useful energy level, what makes the study unique in Switzerland with this high number of measured buildings.

3.3 Weather correction of the measured data

In order to compare the demand (energy certification) and consumption (measurement) of a building, a weather correction of the measured energy consumption is required. This is because energy consumption depends on the weather and the climate, which varies from year to year. In order to be able to compare the measured heat demand with the standard calculation, it must be converted to the reference year's weather. The reference year is the one used in the design calculations and is defined in the Swiss standard SIA 2028 [28]. The weather corrected space heating consumption ($E_{H,Ref}$) is calculated with the equation (1).

$$E_{H,Ref} = HDD_{20/12,Ref} \cdot E_{H,per} / HDD_{20/12,per} \quad (1)$$

where $HDD_{20/12,Ref}$ are the heating degree-days of the reference climate, $E_{H,per}$ is the measured space heating consumption and $HDD_{20/12,per}$ are the heating degree-days of the measuring period. The $HDD_{20/12}$ where calculated in both cases with following equation:

$$HDD_{20/12} = \sum (20^{\circ}C - T_{a,m}), \text{ if } T_{a,m} \leq 12^{\circ}C \quad (2)$$

where $T_{a,m}$ is the daily mean outdoor-temperature.

3.4 Data processing

The measurement data had a resolution of 2 to 10 minutes for all investigated buildings. This data were aggregated to hourly and daily values. The measurement period refers to the year 2015, what guarantees that the properties have in minimum a construction drying period of one year. During processing, the data were examined for measurement errors, outliers, and measurement gaps, and corrected if necessary. Data availability for all objects and measurement parameters was higher than 99%. The data processing is summarized in Fig. 1. For reasons of data protection, all objects were evaluated anonymously.

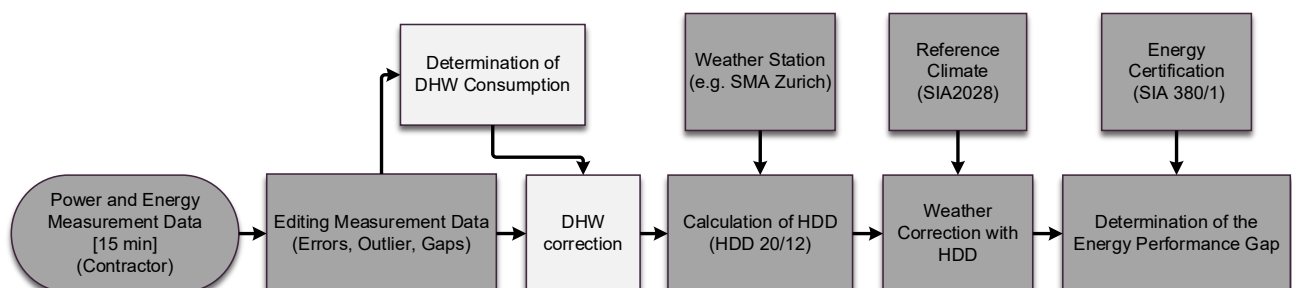


Fig. 1. Flow chart of the data processing procedure

3.5 Correction of the domestic hot water consumption

Of the 65 buildings, 43 (66%) were equipped with separate domestic hot water (DHW) energy meter. For the rest, the DHW share had to be subtracted from the total heat consumption to get the space heating demand. The heat consumption for DHW was estimated by averaging the daily mean power of the heating system when the mean ambient temperature exceeds 23°C. The mean power was then multiplied by the number of hours to get the annual heating demand for DHW. A disadvantage of this method is that all selected measuring points ($T_{amb} > 23\text{ }^{\circ}\text{C}$) occur in the summer months. Both summer holidays and a general increase in hot water consumption in winter can lead to a underestimation of the DHW demand, what is described in the IEA Task44 [29]. Due to this fact, the DHW heating consumption determined from the power characteristic was increased by a constant rate of 15%. The results are displayed in such a way that the reader can see which data points were corrected by the DHW calculation and which were not.

3.6 Reference Building

A MFH was used as the reference building for the simulations. This building corresponds approximately to the average of all examined objects regarding the building parameters. The heating demand with 29 kWh/m²a is 14% lower than the mean value of the investigated buildings. The reason for this is that with the reference building also an analysis for newer buildings can be done. The building has three inhabited stories and six apartments with an energy reference area of total 1'205 m². The shape factor (see Eq. 3) is 1.3 and the window ratio is 25.1% of the energy reference area. The building has a mechanical ventilation with a heat recovery efficiency of 80%. Further details about the reference building can be found in the final report of the project [30]. Fig. 2 shows a 3D image of the building implemented in the simulation software IDA ICE v.4.8.

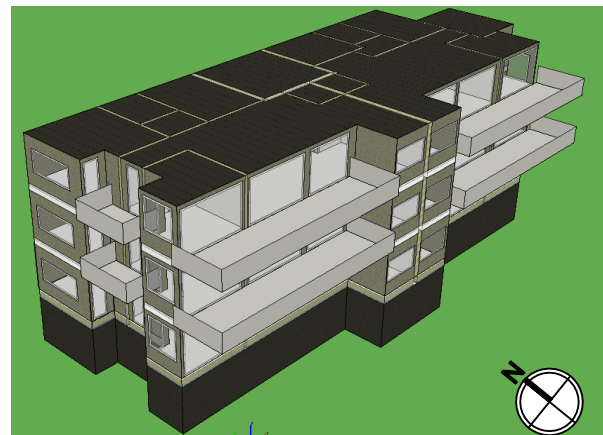


Fig. 2. 3D illustration of the reference building in IDA ICE

4 Results

4.1 Definition of the “Performance Gap”

The term performance gap is critical because it implies that the building is not performing as intended. This gives the impression to the building owner that he has not received what he actually ordered. However, this is not necessarily correct, since a deviation is not only influenced by the construction or the building quality, but also by the operation of the building and the user behavior. In addition, a performance gap can also have its cause in the calculations and assumptions in the standard. The term performance gap is usually associated with increased energy consumption. However, a gap (deviation) can also mean reduced consumption, especially in older buildings.

In this paper we present a new breakdown/structure of the performance gap into causes and effects as shown in Fig. 3. The causes for a performance gap can be subdivided as follow:

The **Ambient-Gap** summarizes all causes due to the climate or the environment, e.g. outside air temperature, shading by trees or other buildings, solar radiation etc.

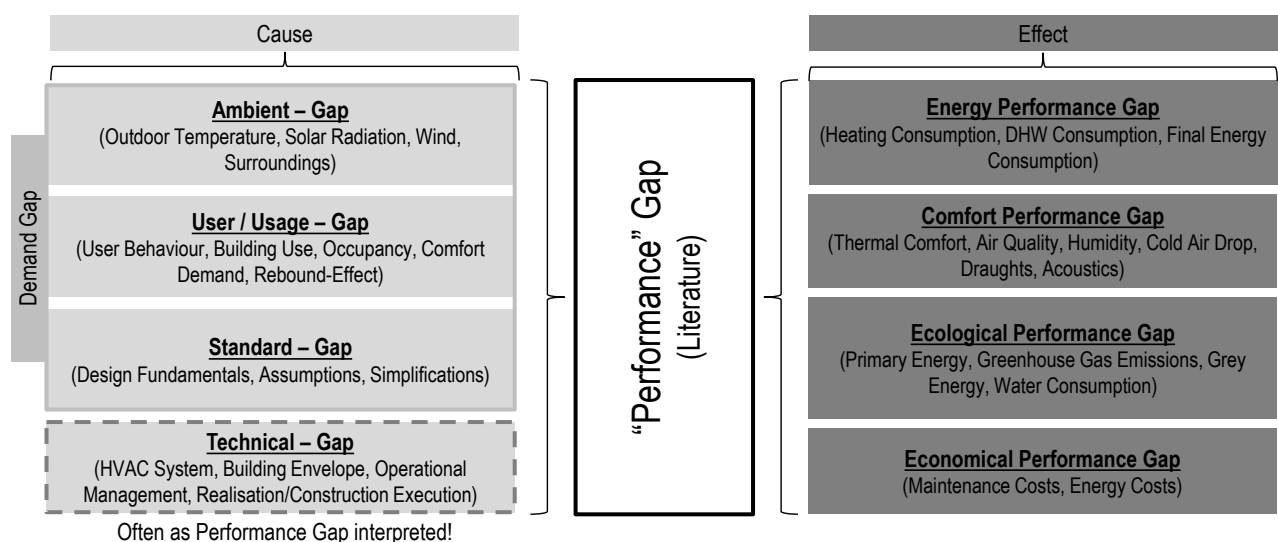


Fig. 3. Classification and subdivision of the term “Performance Gap”

The **User/Usage-Gap** describes the deviation from user behavior or the expected use of the building, e.g. window opening, shading, indoor temperature or the number of habitants in a building.

The **Standard-Gap** describes the deviation between real consumption and the calculated standard demand. Here, incorrect calculation models and methods can lead to wrong results even if all input parameters, like real user behavior were correct. Also wrong assumptions that are standard values provided by the standard, e.g. regarding the efficiency of the HVAC components, can lead to a Standard-Gap.

The **Technical-Gap** describes all causes that occur in connection with HVAC systems or building physics and architecture. This also includes errors in planning as well as errors during the construction. A further important point is the operational management, which includes the setting of the heating curve or the heating limit by the installer or the operator.

The Ambient-Gap, the User/Usage-Gap and the Standard-Gap can be aggregated to the Demand-Gap. Because these gaps lead to a different demand of energy caused by using different heating related parameters or user behaviour. The Demand-Gap can be avoided by using better values and parameters in the calculations or through a sensitisation of the user (e.g. correct window ventilation etc.). In contrast to the Technical-Gap, no physical problems with the building and the HVAC system are the cause.

However, the term performance gap may also be used to describe the deviation in terms of expected comfort or the deviation between measurement and energy policy limits such as primary energy demand or greenhouse gas emissions. Therefore, these deviations were classified under effects in Fig.3. They can be measured and compared with the expectation. The minimization or elimination of these deviations is in the interest of building owners, users, energy contractors or the authorities, as otherwise they can lead to increased operating costs, dissatisfied users or failure to achieve political objectives.

4.2 Analysis of the measured date

4.2.1 Design vs. measurement

In Switzerland, in order to obtain a building permit from the authorities, it is necessary to prove that the minimum energy requirements are met. This is achieved with an energy certificate in which the space heating demand is calculated in a monthly balance according to SIA 380/1. The following results are based on the comparison between the measured weather-corrected annual heat consumption ($Q_{H,meas}$) and the annual heat demand as calculated in the energy certificate ($Q_{H,design}$). An energy performance gap factor (EPGF) was defined for the evaluation. The factor shows if a building uses more heat

than expected (EPGF > 1) or less (EPGF < 1). The EPGF is calculated as follows:

$$EPGF = Q_{H,meas} / Q_{H,design} \quad (3)$$

Figure 4 shows the EPGF for all buildings examined. A differentiation is made between objects with separate DHW measurement and objects with combined measurement.

Four of the 65 objects show a 100 - 115% higher heat consumption than calculated in the energy certificate (EPGF of 2 - 2.15). Three of the houses have a lower heat consumption than planned (up to -6%). The average EPGF for all buildings is 1.44 (+44%). For properties without separate DHW measurement the average is 1.51 (+51%) and with separate DHW measurement 1.4 (+40%). This indicates that the DHW correction may have influenced the results, i.e. it is possible that the energy subtracted for DHW production when measurements were not available may have been lower than the actual energy used for DHW.

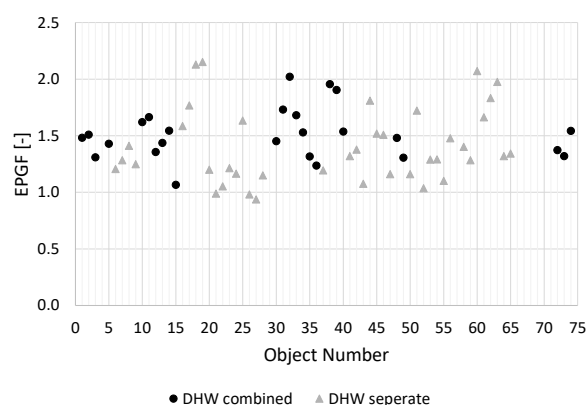


Fig. 4. EPGF for all evaluated buildings with separate and combined monitoring of DWH consumption.

Figure 5 shows the EPGF across all properties with a distinction between the different versions of SIA 380/1 used in the energy certificate. It can be seen that the version of the standard used for the calculation has no major influence on the deviation between measurement and calculation.

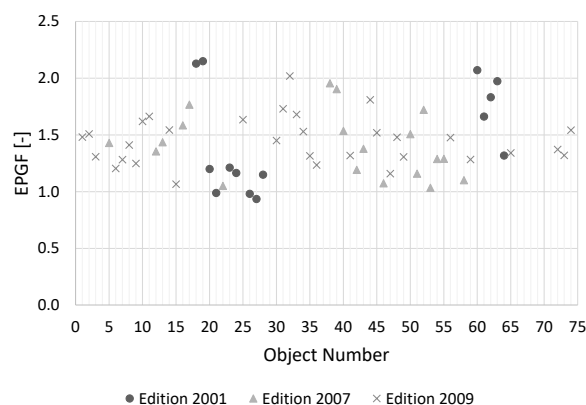


Fig. 5. EPGF for all evaluated buildings with a distinction of the used edition for the energy certification.

The Fig. 6, 7 and 8 show the influence of the year of construction, the window ratio and the shape factor of the building on the EPGF. The building data were taken from the energy certificate. The shape factor (SF) is calculated as follows:

$$SF = A_{th} / A_E \quad (3)$$

where A_{th} is the thermal enveloping surface of the building and A_E is the energy reference area.

The window share as well as the year of construction seem to have no influence on the EPGF. These results contradict a hypothesis of the authors that a larger window share leads to a higher energy performance gap (EPG) as could be concluded from the study of Hässig et al. [14]. On the other hand, the EPGF tends to be higher for objects with a very compact construction ($SF < 1.1$).



Fig. 6. EPGF in function of the year of construction for all investigated buildings.

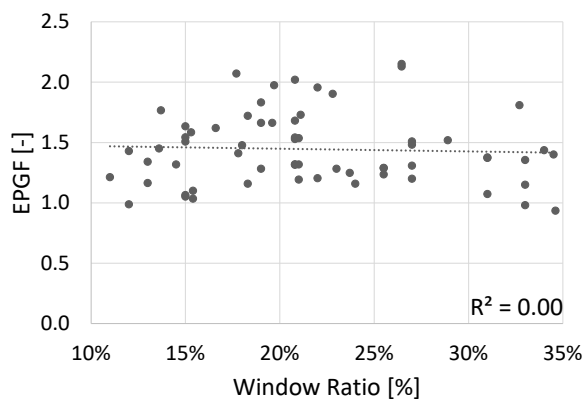


Fig. 7. EPGF in function of the window ratio for all investigated buildings.

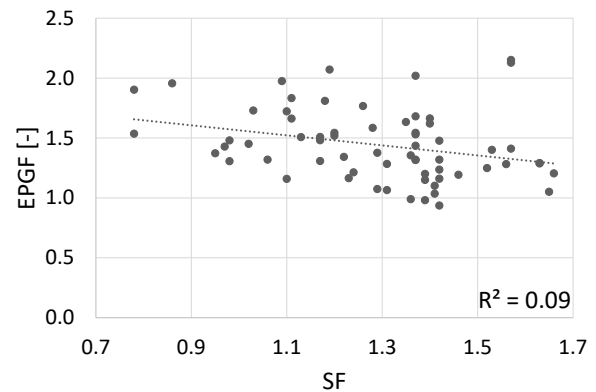


Fig. 8. EPGF in function of the shape factor for all investigated buildings.

4.2.2 HVAC operating parameters

In the following chapter, the influence of heating system parameters on the EPG are examined. Fig. 9 shows the EPGF as a function of the measured space heating flow temperature at the design ambient temperature of $-8\text{ }^\circ\text{C}$. It can be stated that there is a correlation between the EPG and the flow temperature with separate DHW monitoring. Contrary to our expectations, the EPG decreases with higher flow temperature.

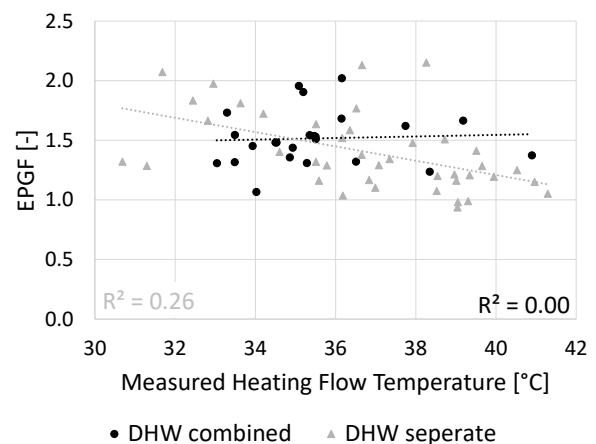


Fig. 9. EPGF in function of the measured heating flow temperature for buildings with separate and combined monitoring of DWH consumption.

Figure 10 examines the EPG as a function of the difference between the planned and measured flow temperatures at the design point. No correlation can be found here in relation to the useful energy. These results suggest that the heating flow temperature is not generally a problem for the increased space heating demand (EPG). One explanation for this could be that an excessive heating flow temperature can be compensated by the room temperature control. As a result, the volume flow is reduced earlier than with a lower heating flow temperature and the heating system is switched off earlier if there is no variable heating power regulation. However, in the case of heat pumps, the higher flow temperature has a negative influence on the electricity consumption (final energy). This is because the

coefficient of performance (COP) decreases with increasing flow temperature and electricity consumption increases accordingly. However, this was not the focus of this study.

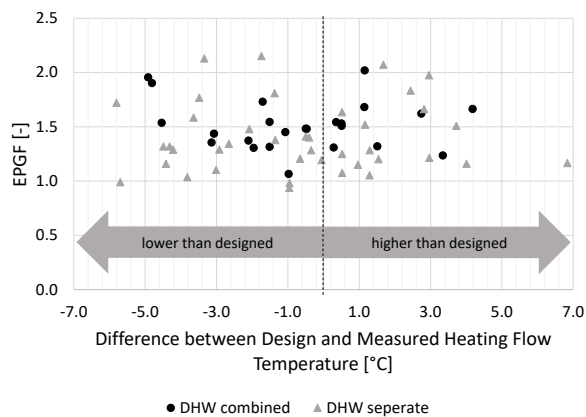


Fig. 10. EPGF in function of the absolute difference of the design and measured flow temperature for buildings with separate and combined monitoring of DWH consumption.

Figure 11 shows that the EPGF is lower for properties, which have overestimated the heating power in the design phase. However, if the heating power is precisely calculated in the design phase the EPGF is higher. However, it may be that because the space heating demand of a building is low, the heating power looks overestimated, and because the space heating demand of another building is higher than expected, the heating power was just enough. In this case, the degree of over-estimation of the heating power would be a result of the energy performance gap rather than the other way around.

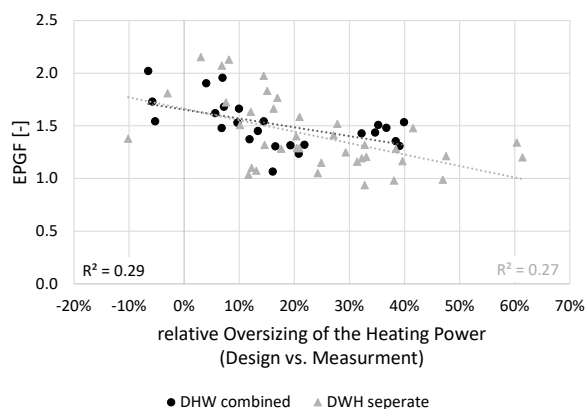


Fig. 11. EPGF in function of the oversizing of the heating power for buildings with separate and combined monitoring of DWH consumption.

A strong positive correlation can be seen in Fig. 12 between the specific heating power and the space heating consumption, both determined from measured date. This relationship is not surprising, as both the heating demand and the heating power are directly dependent on the insulation standard of the building. Surprisingly however, the design values of heating power correlate to a much lower extent, and the ratio between heating

power and space heat consumption is much higher according to the design values (crosses) than according to the field measurements. One reason for this could be that the planner adds a safety margin that is too high.

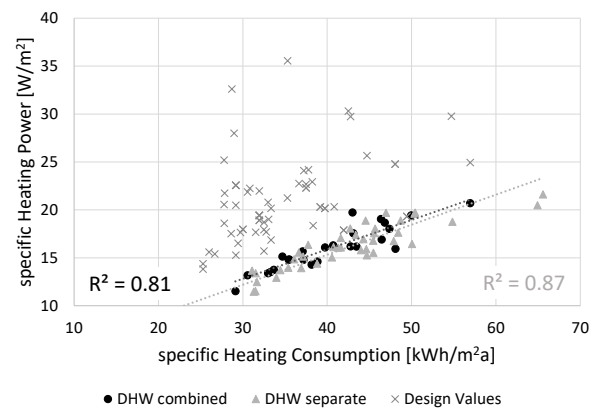


Fig. 12. Specific heating power in function of the specific heating consumption for design and measured values.

One major impact on the EPG has the heating limit, which can be seen in the Fig. 13. The heating limit is a mean outdoor temperature value (usually 24 hours) below the heating system must be switched on in order to maintain the desired indoor temperature. This value depends on the building insulation standard and the user behaviour. In case that the DWH is monitored separately, it can be seen that the higher the heating limit is, the higher the EPGF will be. However, the scatter of the measurement points for the objects with combined DWH measurement is large, which could indicate a distortion of the values by the DWH consumption correction. What is surprising is that none of the buildings has a heating limit below 15.5 °C.

The median for all objects is a heating limit of 17.3 °C. Seven of the 65 MFH's (11%) have a heating limit above 19 °C, which means that these buildings are heated almost all year round.

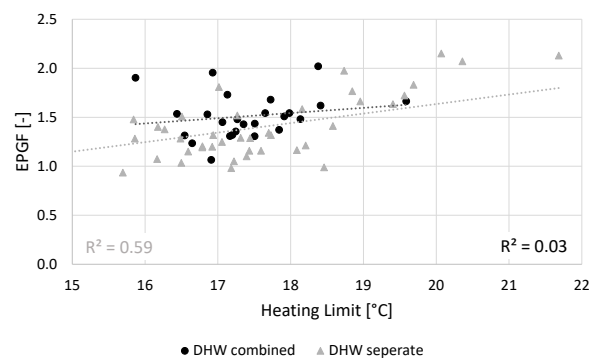


Fig. 13. EPGF in function of the measured heating limit for buildings with separate and combined monitoring of DWH consumption.

4.2.4 Monthly trend of the space heating demand

The detailed evaluation of six buildings shows that the ratio of the monthly space heating consumption in the transition period (spring and autumn) is significantly higher than in the standard calculation (SIA 380/1). This is shown in Fig. 14, where the heating demand ratio in function of the mean monthly ambient temperature is plotted for six measured buildings and a reference building calculated in Lesosai v.2018 (standard calculation SIA 380/1:2009). The energy characteristic of the different buildings in the graph shows that the two properties with the highest EPG (number 51 and 60) have the lowest space heating consumption ratio in winter. In contrast, above an ambient temperature of about 8 °C, they show a significant increase of the space heating consumption ratio. This observation excludes faults or deviations in the building construction as reasons for the EPG, because this would lead to higher heat losses over the whole year.

The reason for the differences in heat consumption in the transition periods and in summer may be high heating limits in combination with missing room thermostat control or high set points of room thermostats. In addition, user behaviour may have a major influence (window opening and window shading).

4.3 Dynamic annual simulations

The internal temperature of the building has a high impact on the thermal energy consumption. The standard calculations assume a room temperature of 20 to 21 °C for apartment buildings. However, it is known from the literature research that room temperatures are generally higher. Since the room temperatures of the buildings were not available as measurement data in the project, the influence of the room temperature as well as the user behaviour with regard to window opening and shading on the space heating demand was investigated with dynamic annual simulations.

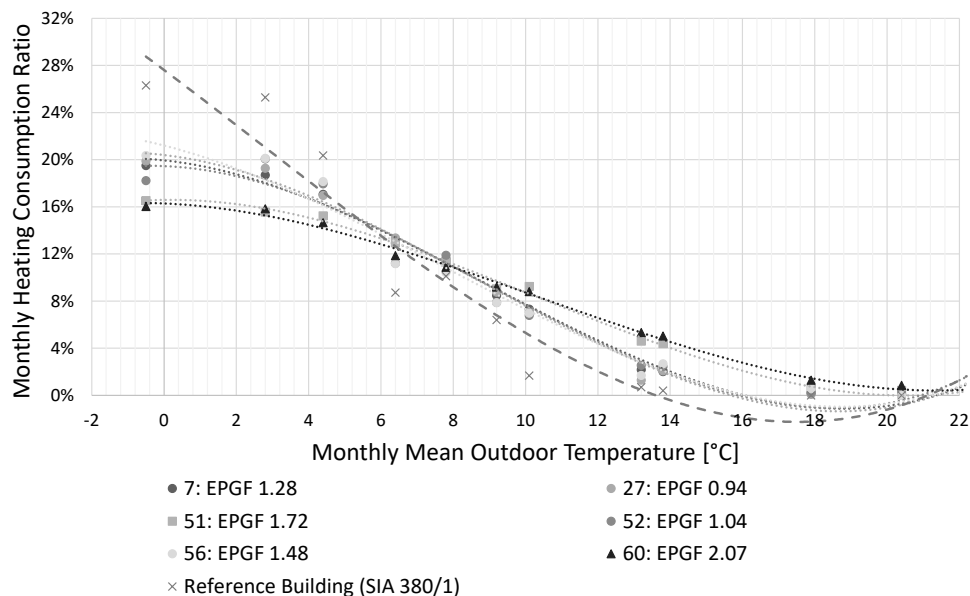


Fig. 14. Fraction of space heat consumption for each of the 12 months of the monitoring period, in function of the monthly mean outdoor temperature. Comparison of six measured buildings with the standard calculation of the reference building.

Figure 15 shows in a histogram for a new MFH (2017) with 26 apartments the mean set point temperature of the thermostat for each apartment in the month of January. The building was evaluated for another project and was not included in the present work [30]. The set point is set by the user with a wheel with marks but no numbers, i.e. the user cannot see the exact temperature he has set. Half of the apartments have a set point temperature of 24 °C and more. The mean measured room set point temperature in the building is 23 °C.

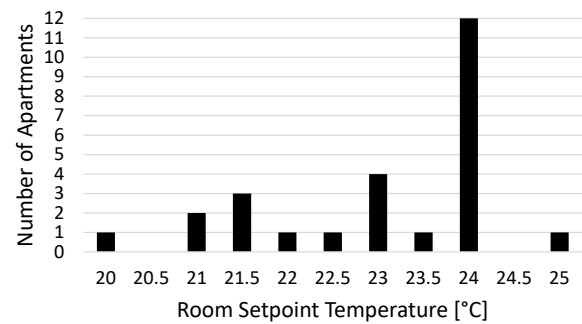


Fig. 15. Histogram of the thermostat set point temperatures of different apartments of an MFH.

The effect of higher room temperatures on the space heating demand is shown in Table 2. For a MFH reference building (see 3.6 Reference Building) the space heating demand with different room temperatures was calculated in Lesosai v.2018 (according to SIA 380/1:2009) and dynamically simulated with IDA ICE v.4.8. On average, the well insulated building has a higher annual space heating demand of 14.4% per Kelvin higher room temperature when simulated with IDA ICE. When calculated with Lesosai on a monthly base the annual over-consumption is 12.2%/K.

From this we conclude that a good part of the EPG may be explained by higher room temperatures. We assume that this effect may be responsible for an energy performance gap of about 30 - 40 percentage points.

Table 2. Simulated and calculated space heating demand of the reference building with different room temperatures.

Room Temperature	Space Heating Demand [MJ/m ²]	
	IDA ICE	Lesosai (SIA 380/1:2009)
21 °C (Reference)	82.2	117.4
22 °C	93.4 (+13.6%)	131.1 (+11.6%)
23 °C	105.0 (+27.7%)	145.5 (+23.9%)
24 °C	117.6 (+43.1%)	160.4 (+36.6%)

In addition to the room temperatures, also the window opening and the shading of windows has an impact on the energy demand. Therefore, the annual simulations were done with different variants of shading and window opening. Deep analysis of selected buildings in the project, which have been published by Mojic et. al [31], show that the following control of shading and window opening leads to results that are more realistic than the control, which is used in the standard calculations (SIA 380/1):

- **Plausible shading control:** when the room temperature reaches 20.5 °C and the radiation reaches 200 W/m² on the façade, the g-value of the window is reduced to 0.06.
- **Plausible window opening control:** In the transition and summer period (March to October), one window per apartment is tilted (10% of the area is open) in the night (20.00 – 07.00).

The simulation results in Figure 16 show that with the plausible user behaviour and with room temperatures of 23 °C the monthly heating demand ratio of the reference building fits better to the real measured buildings (Figure 14) than the ideal user behaviour which is based on the standard parameters. The total space heating demand simulated with IDA ICE in the case of the ideal user behaviour is 21.5 kWh/m². In the case with plausible user behaviour it is 38.3 kWh/m². That leads to an EPGF of 1.78, respectively to an over-consumption of heating energy of 78% because of user behaviour that differs from the assumptions in the standard calculation.

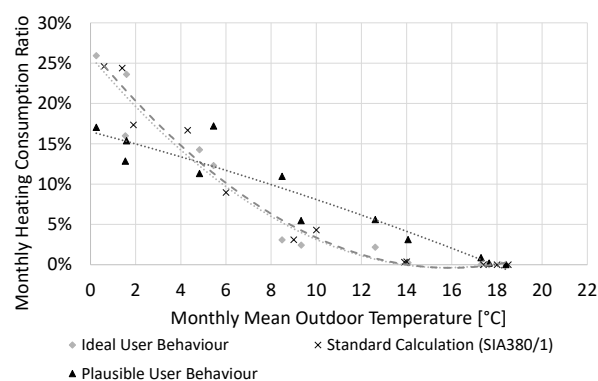


Fig. 16. Comparison of the monthly mean heating consumption ratio for simulation with different user behaviour.

5 Discussion

In order to determine the energy performance gap, the weather-adjusted space heating consumption was compared with the calculated heating demand according to SIA 380/1 (energy certificate) with standard conditions. This comparison is also frequently used in other studies. The difficulty with this comparison is that the user behaviour in the calculation of the energy certificate usually does not correspond to reality. The primary aim of an energy certificate in accordance with SIA 380/1 is to prove that the legally required thermal engineering standard has been met. Therefore it is already pointed out in the standard itself that a prediction of the presumed heating consumption should not be carried out with the standard parameters, but with object-specific real settings and effective use. However, it is not possible to determine the real conditions of use without great effort. For example, the determination of the sun protection (shading) and ventilation behaviour is very time-consuming in practice. Even the procurement of the energy certificates is - as the experience from the present project shows - very complex. A complete recalculation according to "SIA 380/1 - Optimization" with more real conditions of use would mean hardly justifiable expenditure for a larger portfolio. Therefore, for such broad evaluations as in the present project, the determination of an energy performance gap is realistically only possible in comparison to an energy certification, despite methodical limitations.

The results show, that building parameters such as the window ratio and year of the construction do not seem to have a significant impact on the energy performance gap. Much more important is the user behaviour regarding room temperature, window opening and window shading. Why the user behaviour varies so much could not be investigated in this project, user surveys would be necessary.

A frequently lowered sun protection can be justified by the fact that the inhabitants want to protect themselves from the looks of the neighbours, room overheating, or however because the sun blinds. Higher room temperatures are not always desired, but can also be a consequence of comfort problems, which are caused for example by missing hydraulic adjustment of the heating

distribution or by cold room surfaces, usually walls or floors. High room temperature set points may be the result of problems in setting the optimum room temperatures or inadequacies in the flow temperature or heating limit control. It can be assumed that the dissatisfaction with cold room temperatures is answered with higher set point values, but that individual days with higher temperatures than actually desired do not necessarily lead to a reduction in the set point values but may under certain circumstances result in open windows. The influence of user behaviour on the space heating demand was only determined for a simulated reference building and not for the monitored buildings. However, the reference building corresponds approximately to the average of all examined objects with regard to the relevant building parameters. Depending on the specific object, however, the effect on the results will be somewhat different. In addition, user behaviour in a passive house, for example, is likely to have a much greater relative effect on space heating consumption. Nevertheless, a passive house will have a lower absolute consumption than the reference building because the better thermal envelope of a passive house in combination with efficient comfort ventilation leads to significantly lower transmission and infiltration losses in winter.

The user behaviour regarding room temperatures, window shading, and window opening will be investigated in a next project with the synonym „VenTSol“ from 2019 to 2021.

6 Conclusions

The investigations show that the design of the heating power is very often too high. This has an influence on the efficiency of the heating system as well as on the investment costs. The connection between space heating demand and heating power must be communicated on a broad level and integrated into the education of the professionals.

Further findings from the study are that the heating limits are significantly higher than one would expect for these building standards. Some of the buildings are heated all year around. By contrast, it is interesting to note that some buildings have lower heating flow temperatures than originally designed, which is surprising. One reason for this may be that the energy contractor is interested in operating his systems in the best possible way, e.g. the COP of a heat pump decreases with higher heating flow temperature.

The results from simulations show, that the user behaviour has a major impact on the energy demand, especially when the building has a very good insulation standard. Surprisingly, the energy performance gap (space heating) is not a result of a high demand over the whole heating season but appears especially during the transition period (spring, summer and autumn). This is most likely caused by the window opening and shading behaviour of the user, which differs from the standard assumptions. A further effect of this finding may be that the standard simulation profiles underestimate, for

example, the benefits of solar thermal systems, since space heating consumption is higher in the transition period where the solar irradiation is higher compared to the winter period. This may lead to an underestimation of solar fractions for solar assisted space heating.

A separate evaluation of the DHW consumption is always to be preferred, because a combined monitoring can hinder the exact determination of the space heat consumption.

The reasons for the energy performance gap could not be fully clarified in this study. However, various clues and significant correlations could be identified. Thanks to the detailed analysis of the measured data in combination with simulations, the influence of the users on the space heating consumption can be estimated better. The results can help to evaluate the measurement data collected in the future through increased monitoring in a more targeted and possibly automated way.

Knowledge of the effective demand compared to the theoretical demand also helps, for example, in the correct dimensioning of geothermal probes for heat pumps. In the building pool investigated, a high relative additional consumption corresponds to a high absolute additional consumption. For this reason, the results are also relevant for statistics and forecasts on energy consumption and CO₂ emissions in buildings throughout Switzerland. Regardless of why the buildings require more space heating, an increase in useful energy consumption has a direct influence on the final energy consumption. Despite the energy performance gap, houses for which a lower heating demand was forecast tend to have a lower heating consumption.

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