Energy consumption of high-performance buildings: Design vs. Reality

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Abstract. Studying the performance of highly efficient buildings is crucial for future policy, for example to inform decision making about whether to pursue further thermal improvement of buildings (insulation) or to rather foster investments in renewable resources. For this purpose, reliable values of the energy demand of new and retrofitted buildings are needed. However, there is evidence of a significant Energy Performance Gap (EPG) in buildings, defined as the difference between measured and calculated energy consumption. The objective of this paper is therefore to quantify the EPG in high efficiency buildings in Switzerland. The EPG was studied for 56 residential buildings, including various construction standards (Minergie, Minergie-P, and Minergie-A) and building types (new and retrofitted). The Minergie indexes were used as theoretical consumption, thereby representing the total final energy consumption for all needs of the buildings. These values were compared to data based on measurements. For the buildings in the sample the analysis yields a negative EPG of -14% (i.e. the median building consumes slightly less than its standard), indicating that the most efficient buildings are more robust to the EPG. However, this finding could be partly a consequence of the small sample used and its characteristics.

1. Introduction

Buildings are responsible for 40% of the total final energy consumption in the European Union as well as in Switzerland [1,2]. Whilst the importance of energy efficiency to meet the environmental targets of the building stock is widely recognised, there are still challenges on how to track the energy consumption of buildings, for example whether, and if so, how to consider the impact of occupants, the building fabric and heating systems on the energy performance. An important step forward was the introduction of the energy performance certificate for buildings [3]. In practice, the performance certificate reports the expected energy consumption if the building is used in compliance with the standards [4]. The reliability of these performance certificates as well as of private labelling systems such as Breeam [5] or Minergie [6], and more generally of any calculation-based building performance evaluation, is critical for the level of energy costs for building inhabitants as well as for achieving future energy targets [7] whenever the objectives are based on these expected performance levels. This consequently leads to the question of whether the calculated energy performance levels are realistic.
Previous research provided evidence of a significant Energy Performance Gap (EPG) in buildings, defined as the difference between measured and calculated energy consumption [8–11]. There is a broad agreement in the literature that buildings with poor thermal performance tend to consume less than predicted. Vice versa, buildings with high thermal performance tend to consume more than predicted [12,13]. However, it is unclear whether and to what extent these findings on high efficiency buildings can be applied to Switzerland, given the overall thermal performance of the Swiss buildings differ to that of other European countries [14].

This paper studies the EPG in high-performance buildings in Switzerland. Studying the real performance of these highly efficient buildings is important for future policy, for example as support for deciding about whether to pursue further thermal improvement of buildings (insulation) or to rather foster investments in renewable resources. For this work, Solar Agentur data is used, which consists of new and recently renovated buildings that can be considered as examples of best practice in terms of energy performance. On the basis of measured data it is established whether the consumption meets Minergie targets and the size of the EPG is calculated. The size of the EPG is then distinguished by type of label (Minergie, Minergie-P, Minergie-A) and building types. It is tested whether the Minergie-P buildings, with their particularly high insulation level, show significantly different performance gaps than other types of labels.

2. Method
The energy performance gap is obtained using the definition of the difference in consumption as a proportion of the theoretical consumption for a given building [8]:

\[
EPG \% = \frac{Actual \ consumption - Theoretical \ consumption}{Theoretical \ consumption} \times 100\%
\]

Equation 1

The EPG in this paper is calculated as difference between the actual total final energy use (for all applications combined) and the calculated target for final energy, both in kWh/(m²y). The theoretical consumption used to calculate the EPG is approximated using the target of each Minergie standard [6], and therefore does not change for each building, but is a fixed value below which all buildings should be. This approach is chosen because the theoretical consumption data for each building is not available in the Solar Agentur database. This approximation has consequences for the interpretation of this EPG. Strictly speaking, it does not indicate the over/under-consumption of a building compared to its theoretical consumption, but rather its over/under-consumption compared to that of the standard within which it is found.

There are six different Minergie targets, one for each of the three Minergie standards (Minergie, Minergie-P, Minergie-A) and for both new and retrofitted buildings. These targets are expressed in terms of weighted final energy, calculated by weighting the different energy carriers used in the building using a national factor [15], and subsequently summing them. In order to ensure a common approach with previous studies, the weighted final energy values have been recalculated in terms of total final energy without weighting, to be then able to compare with the actual consumption (always expressed in final energy).

3. Data
The Solar Agentur database contains the actual final energy consumption of 149 buildings, with various destinations of use (residential, commercial, schools etc.). This data is usually provided by the building owner at the moment of the application to the Swiss Solar Prize, justified through energy bills. Furthermore, the jury awarding the prize must verify this data with each local energy provider. The electricity providers must confirm the total amount of electricity produced by PV (if possible for them), the fraction that is injected into the grid, and the amount of electricity that is purchased from the grid. These three factors are used to calculate the total electricity consumption of the building, representing
the sum of all needs (space heating, domestic hot water, ventilation, lighting, appliances). When a different energy carrier than electricity is used (e.g. biomass), the owner must report the amount of fuel used through bills. Regardless of the type of heating system, the energy consumption is always given as total final energy consumed [kWh/y].

The scope of the analysis only considers residential buildings, reducing the sample size to 115 buildings. Some of these buildings are equipped with biomass or gas boilers, but it is impossible to know the share coming from the different energy carriers to apply the proper weighting factor (i.e. the amount of gas used for the heat supply and the amount of electricity used for lighting and appliances). Therefore, only buildings with heat pumps are analysed, as the available information in regard to total final energy consumption is considered reliable only in this case, further reducing the sample size to 78. Finally, to ensure the reliability of the data, only those buildings for which consumption had been measured and verified for more than 120 days are kept, in order to reduce the risk of unprecise estimates when scaling the results to the entire year, e.g. due to seasonality. This last filtering step reduces the final sample to 56 buildings.

4. Results
Since the Minergie targets are different for new and retrofitted buildings, these categories are treated separately. Some buildings that respect only the MoPEC [16] limits are also shown, as many of the buildings in the Solar Agentur database do not have the Minergie certification even though they meet the Minergie energy performance targets (it should hence be noted that the MoPEC buildings discussed in this work have a much better thermal performance than average MoPEC buildings). These MoPEC buildings (including both new and retrofitted buildings) are compared with the Minergie ones. It is important to highlight that actual consumption is expressed in terms of final energy and represents the total consumption (including electricity) of the entire building. Keeping this in mind and regardless of any consideration of the EPG, the energy consumption of these buildings is remarkably low, as presented below in Table 1 and Table 2.

4.1. New buildings
For the new buildings (28 buildings) a median EPG of -13% is found (i.e. lower consumption than targeted) while the mean is -3.9%, reflecting the presence of few buildings which consume considerably more than their targets. The results per building are presented in Figure 1.

![Figure 1: Actual final energy consumption per new buildings in the Solar Agentur sample.](image-url)
Table 1: Energy performance gap per building standard in new buildings.

| New building standard | Number of buildings | Mean consumption [kWh/(m²y)] | Median consumption [kWh/(m²y)] | Mean EPG [%] | Median EPG [%] |
|-----------------------|---------------------|-------------------------------|-------------------------------|--------------|---------------|
| MoPEC 2014            | 5                   | 38                            | 30                            | 6.9          | -15           |
| Minergie              | 5                   | 41                            | 33                            | 15           | -6.8          |
| Minergie-P            | 14                  | 29                            | 29                            | -11          | -12           |
| Minergie-A            | 4                   | 30                            | 30                            | -15          | -16           |

In Table 1 the EPG and the actual consumption per building standard are reported, together with the number of buildings used to calculate the values. Given the small number of buildings in each standard, this EPG must be interpreted with great caution, as it is probably not representative of the entire Minergie stock.

The results for the Minergie-P buildings (median EPG = -12%, meaning that the actual consumption smaller than the calculated) and Minergie-A (median EPG = -16%) indicate these buildings, with their particularly stringent design requirements, show clearly better performance (overfulfilment of targets) than other types of standards [11].

4.2. Retrofitted buildings

In the sub-sample of retrofitted buildings (also 28 buildings) a median EPG of -16% (mean -12%) is found, meaning an actual consumption smaller than the calculated. The results per building are presented in Figure 2 and are comparable to the ones for new buildings. A similar trend is found for the Minergie-P retrofits, all of which performed better than their target with a negative EPG of -18%, (Table 2), and for the Minergie-A retrofits, all of which are below their target with an EPG of -5.3%. Again, it is important to highlight that these findings are based on a very limited sample the energy performance of Minergie-P and Minergie-A are similar (somewhat better for Minergie-A) and clearly better than Minergie (see Table 2).

![Figure 2: Actual final energy consumption per retrofitted buildings in the Solar Agentur sample.](chart)
Table 2: Energy performance gap per building standard in retrofitted buildings.

| Retrofit building standard | Number of buildings | Mean consumption [kWh/(m²y)] | Median consumption [kWh/(m²y)] | Mean EPG [%] | Median EPG [%] |
|---------------------------|---------------------|-------------------------------|-------------------------------|-------------|--------------|
| MoPEC 2014                | 15                  | 55                            | 60                            | -6.6        | 3.0          |
| Minergie                  | 3                   | 56                            | 45                            | -3.8        | -23          |
| Minergie-P                | 7                   | 37                            | 43                            | -29         | -18          |
| Minergie-A                | 3                   | 33                            | 34                            | -7.5        | -5.3         |

A partial explanation of this behaviour of the Minergie buildings can be given by the way in which these two standards, Minergie-P and -A, are designed. The Minergie-A standard, despite having the lowest Minergie target, focuses on the quality of energy to minimize the emissions per kWh (kgCO₂-eq/kWh), with auto-production as a key strategy. In terms of performance of the envelope, however, it has the same requirements as that prescribed by the new MoPEC 2014 [16]. The Minergie-P standard, despite its higher target than Minergie-A, focuses on reducing the heating demand, following the German Passivhaus model [17]. The envelope performance must be 30% better than those prescribed by the MoPEC [6]. These findings are consistent with the ones of previous studies on Minergie buildings that indicated a small EPG or even an outperformance compared to the standards (negative EPG) [18,19].

5. Conclusions
This work investigates the EPG in high performance residential buildings, specifically those with the Swiss Minergie certification. Minergie buildings with actual consumption from the Solar Agentur database are studied. The analysis compares Minergie, Minergie-P, and Minergie-A standards to determine the relation between the label type and the EPG, by converting the label target values to final energy. After filtering of the dataset, 56 buildings equipped with PV and heat pump are evaluated. The buildings in the sample display very high performance.

Regarding the EPG, the findings seem to confirm the higher performance of Minergie-P buildings, with an EPG of -12% for new construction and -18% for retrofit, and also of Minergie-A buildings with an EPG of -16% for new construction and -5.3% for retrofit. However, even if the deviation in percent terms seems significant, in absolute values the actual consumption is below the target by only 4 kWh/(m²y) for Minergie-P buildings and by 6 kWh/(m²y) for Minergie-A (for the total energy needs of the building).

The design of the Minergie-P and -A labels may be the cause of these exceptional results, e.g. presence of mechanical ventilation, summer thermal protection, and airtightness measurement required. Moreover, for Minergie-A buildings, the yearly production of the photovoltaic system must cover the all the energy needs of the building.

Although only a small sample can be considered here, this research provides further support for the hypothesis that very high efficiency buildings (Minergie-P) are less affected by the EPG and that remarkably high energy efficiency levels can realistically be achieved. However, it is important to highlight that these results refer to prize-nominated buildings and therefore represent a best-case scenario. This calls for further studies of buildings representing more common conditions and with higher sample sizes. It should be also noted that the energy demand of a small number of buildings significantly exceed their targets, which highlights the need for operational monitoring of buildings’ energy consumption. In addition to the identification of the causes of over-consumption, systematic monitoring over the building life cycle helps achieve the objectives set in the design phase and the execution of similar projects in the future.
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