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GAPxPLORE: Energy Performance Gap in existing, new, and renovated buildings

Learning from large-scale datasets

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Executive Summary

Introduction

Buildings are responsible for 40% of the total final energy consumption in Switzerland while 70% of the final energy used in 2016 in the residential sector is related to space heating. In order to reduce this consumption and in line with the other EU energy policies, the Swiss Federal Council has been developing and implementing the Energy Strategy 2050 (ES-2050) since 2011. The ES-2050 is based on three strategic objectives: increasing energy efficiency, increasing the use of renewable energy, and withdrawal from nuclear energy. For residential buildings, this translates for final energy to be reduced by 46% and CO_2 emissions by 77% until 2050 according to the "New Energy Policy". It is therefore crucial for the success of energy and climate policy to accurately estimate the energy saving potential of the building stock. For this purpose, reliable values of the energy demand of existing and retrofitted buildings are needed. These values are generally established either through measurement or by calculation using a model. However, there is evidence of a significant Energy Performance Gap (EPG) in buildings, defined as the difference between measured and calculated energy consumption. There is a broad agreement in the literature that buildings with poor thermal performance (low energy rating) tend to consume less than predicted, i.e. less that calculated under standardized conditions. Vice versa, buildings with high thermal performance (high energy rating) tend to consume more than predicted.

Several European projects have had the objective to monitor the actual performance of buildings and to reduce the EPG including EPISCOPE (Germany), TRIME (Netherlands), TRIBUTE (Ireland), HIT2GAP (France), UserTEC (Denmark). However, these projects are limited to EU countries and exclude Switzerland. It is unclear whether and to what extent these findings can be applied to the Swiss building stock. Our project GAPxPLORE which covers thousands of buildings is the most comprehensive study so far conducted in Switzerland and aims to offer statistically representative results, providing valuable insight for policy makers and other stakeholders.

Goals and section contents

The GAPxPLORE project aims to evaluate the EPG in the Swiss building stock. It studies how the EPG is distributed among the building typologies (performance level and age). Large-scale datasets from a range of sources containing calculated and real energy consumption data of buildings are analysed. GAPxPLORE also investigates the Energy Savings Deficit (ESD), defined as the difference between expected and achieved energy consumption reductions in renovated buildings. The focus lies on the final energy consumed for heating and domestic hot water in residential buildings. Four data sources were used. First is the Swiss Cantonal Energy Certificate for Buildings (CECB) database, which provides a sample of 50 000 buildings. Second, the Swiss Solar Agency data was used, which was collected from applications for the Swiss Solar prize and consists of new and recently renovated buildings that can be considered as examples of best practice in terms of energy performance. This data includes measured energy consumption information for roughly 150 buildings. The third dataset represents the Swiss Minergie buildings. The fourth dataset is the Energo platform containing measured energy consumption of buildings across Switzerland. However, only a part of each of these datasets was ultimately used after having cleaned and filtered the data (e.g. removal of implausible values). This report consists of one introductory section followed by six sections that present the analyses.

- **Section 2** presents a literature review on the EPG in Europe and Switzerland with the objective of creating an overview of existing findings for Switzerland and to compare these with EU countries.
- **Section 3** explains the data sources used for the analysis and assesses their representativeness. The preliminary cleaning and filtering of the data is presented, as well as the samples sizes used.
- **Section 4** studies the EPG in the Swiss building stock using the CECB database. This provides statistically representative results of the EPG size and findings by building categories.
- **Section 5** studies the correlations between the expected and achieved savings obtained through building retrofit using a sub-sample of the CECB dataset.
- **Section 6** studies the EPG in high efficiency buildings by type of standard (Minergie, Minergie-P, Minergie-A) and by building type. The aim is to understand how the EPG of Minergie-P buildings compares to the EPG found for other labels. This task uses the datasets provided by the Swiss Solar Agency, Energo, and Minergie.
- **Section 7** presents case studies on Minergie buildings from the Energo database. The analysis includes the design phase calculations and post-commissioning, maintenance and optimisation in order to explore the causes of the EPG.

Finally, **Section 8 and 9** present the limitations and the conclusions.

Results

The review of existing research on the Energy Performance Gap has shown that there are a number of different definitions for calculating the EPG, and a large range of values reported. Three definitions can be distinguished, which differ in the way how the calculated consumption (for later comparison with the actual consumption) is modelled: a regulatory, static, and dynamic performance gap. The regulatory performance gap, that compares the performance of a building under standardized national conditions to measured energy use, is the most widely used type of EPG and it plays an important role in this study as well. The variety in metrics and terminology and the resulting challenge of drawing sound conclusions has been identified as an obstacle to closing the EPG. To do so, it would need to be always very clear what is included in the consumption values that are compared and what type of energy is compared (i.e. heating demand or final energy for all energy services in a building). There is some lack of clarity in Swiss literature and legislation, as the building owner or inhabitant is consuming (and paying for) final energy at the meter, while the energy labels (CECB and Minergie) and the related legislation/norms refer to the “weighted final energy” calculated using national factors. These factors, which are collectively defined by the cantons, reflect the cantonal energy policies rather than the performance of the building envelope or heating system.

The project findings confirm the existence of an EPG for Swiss residential buildings, with a median of -11% (i.e. the median building performs slightly better than expected). The total actual consumption of final energy for the entire residential building stock is 6% lower than calculated. This value differs from the median EPG (-11%) as the total consumption delta across the building stock is the result of weighting of the EPG values per building with the total ERAs by building class, and the specific energy consumption per meter square. Furthermore, the data analysis shows a strong correlation between energy rating and EPG. For low performing G-labelled buildings, a negative EPG of -40% was found, while for the higher performing buildings with B-label a positive EPG of +12% was determined. These results support previous findings in the literature according to which higher performance buildings are consuming somewhat more than predicted while lower performance buildings are consuming significantly less than predicted.

A subsample of the CECB dataset was then generated which consisted of residential buildings that had a CECB certification both before and after renovation in order to investigate the relationship between the expected and achieved savings obtained through energy retrofit. This subsample included 1172 buildings. For all these buildings, the Energy Savings Deficit was calculated. Two versions of the ESD have been proposed in this study: the regulatory ESD (ESDr) using the theoretical savings (based on theoretical energy consumption before and after retrofit) as the expected savings, and the anticipated ESD (ESDa) using the anticipated savings (difference between actual consumption before retrofit and theoretical consumption after retrofit) as the expected ones. Independently of the calculation method, it was found that despite an increase of the heated area by 7% in the course of energy retrofit, total final energy use and CO_2 emissions for thermal purposes was halved in the building sample.

The ESDr and ESDa were calculated for the whole subsample, resulting in a median ESDr of 37.3% and a median ESDa of 3.60%. The result for the ESDr implies that based on the theoretical values, only 62.7% (100% - 37.3%) of the expected savings are actually achieved. Instead when using the anticipated values (ESDa), 96.4% (100% - 3.60%) of the expected savings are actually achieved. Moreover, it was found that the ESDr increases with the label improvement, meaning that the energy savings obtained through deep retrofit are about half of the calculated ones. The ESDa, however, showed the opposite trend, decreasing with the increase of the label improvement, until it becomes even negative for very deep retrofit (which means that more energy is saved than anticipated).

Finally, the EPG was studied in a sample of 56 high-performance buildings, focusing on the difference in EPG among the various Minergie standards (Minergie, Minergie-P, and Minergie-A). The Minergie indexes were used as theoretical consumption, thereby representing the total energy consumption for all needs of the buildings (and differing from the theoretical consumption defined in previous parts of the study, which only included space heating and domestic hot water). A median EPG of -14% was found. The results 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/(m^2y) for Minergie-P buildings and by 6 kWh/(m^2y) for Minergie-A (for the total energy needs of the building).

For the case studies presented in Section 7, the EPG for heat consumption ranged from -44% to +93% and the EPG for electricity consumption ranged from -2.9% to +132%. The main reasons for the EPG for heat are i) the higher temperature of space heating and of the hot water primary circuit compared to the standard values as well as ii) window opening for long periods of time causing temperature drops. The main reasons for the performance gap in electricity are incorrect time schedules of the ventilation systems and high energy consumption for appliances. It was found that one of the greatest uncertainties in determining a building's EPG is not the collection of actual consumption data but the determination of theoretical consumption. In the case studies analysed, between 44% and 76% of the theoretical consumption was calculated with parametric indices and the remaining energy consumption was established in a more precise but non-homogeneous way (e.g. sometimes on an hourly, monthly or other time basis). In fact, the energy calculations carried out during the design phase of a building do not have the objective of forecasting the final total consumption but of evaluating the efficiency of the main design choices and their compliance with energy requirements by respecting the limits established by national standard or laws.

Conclusions

GAPxPLORE confirmed the existence of an EPG in the Swiss residential sector, with buildings with low thermal performance tending to consume less than predicted (negative EPG) and buildings with high thermal performance tending to consume marginally more than predicted (positive EPG). The observed values are smaller than those reported in existing case studies in Switzerland, partly because this is the first stock-level assessment (rather than focusing on small numbers of high efficiency buildings). A further reason may be that building owner applying for a certificate may pay more attention to energy efficiency than the average owner. Finally, the subsamples of the CECB data used for this analysis may not be fully representative of the Swiss building stock for other reasons (e.g. cantonal representation, filtering etc.). It is important to highlight that the different values of the EPG found for low and high energy rating imply very different levels of final energy consumption, as one percent point represents very different energy consumption values in terms of kWh/(m^2y) for the low rating compared to the high rating. For this reason, care should be taken when interpreting the percentage values for EPG for different energy labels.

The results on the energy savings deficit for retrofitted buildings suggest that the regulatory ESD (ESDr) is not a good indicator of the quality of an energy retrofit, as most of the deficit is due to an over-estimation of the consumption of the building prior to retrofit. Therefore, the ESDr reflects the error in the calculation of the theoretical savings rather than the quality of the retrofit itself. Conversely, the anticipated energy savings deficit (ESDa) proves to be a clearly more reliable indicator for judging the success of a retrofit in view of the small error in absolute terms (only 3.60%). The ESDa has the additional benefit that it allows to indicate significant deviations between Anticipated and Actual savings and therefore helps to identify system or operational failures (i.e. if the building does not perform as anticipated, this is likely related to a practical issue rather than an error in the calculation). Finally, the small value of ESDa found suggests that the overall quality of the energy retrofitting performed within this sub-sample is high, indicating, *inter alia*, that on-site workmanship is not a major problem in Switzerland. This analysis furthermore positively reassures that demanding energy savings objectives are often achieved, a finding that also policymakers and investors might find encouraging while keeping in mind that this analysis was based on a relatively small subset of the CECB dataset.

For the Minergie buildings, the analysis yields a negative EPG of -14% (i.e. the median building consumes slightly less than its standard), which provides further support for the initial hypothesis that the most efficient buildings are more robust to the EPG (for the A-label buildings in the CECB sample an EPG for space heating and domestic hot water of -6.2% was found). However, this finding could be partly a consequence of the small sample used (56 buildings) and its characteristics.

To conclude, the finding for the entire Swiss residential building stock, according to which the total actual consumption of final energy is 6% lower than predicted, is reassuring but it is in contrast to some previous studies relying on case studies in Switzerland. Our finding is based on the CECB sample and further research would be required to understand whether the buildings included in this sample perform better than average in Switzerland. Similarly, the overall limited EPG found for high performing buildings is reassuring, with Minergie-P and Minergie-A buildings even outperforming the theoretical values. In view of the origin of the data (Swiss Solar prize) and the smaller sample size, these findings should not be generalized, while nevertheless showing that remarkably high energy efficiency levels can realistically be achieved.

Résumé exécutif

Introduction

Les bâtiments représentent 40% de la consommation finale totale d'énergie en Suisse, tandis que 70% de l'énergie finale utilisée en 2016 dans le secteur résidentiel est liée au chauffage des locaux. Afin de réduire cette consommation et conformément aux autres politiques énergétiques de l'UE, le Conseil fédéral élabore et met en œuvre la Stratégie énergétique 2050 (ES-2050) depuis 2011. L'ES-2050 repose sur trois objectifs stratégiques : accroître l'efficacité énergétique, augmenter l'utilisation des énergies renouvelables et sortir du nucléaire. Il est donc crucial pour le succès de la politique énergétique et climatique d'estimer avec précision le potentiel d'économie d'énergie du parc immobilier. Pour ce faire, des valeurs fiables concernant la demande en énergie des bâtiments existants et rénovés sont nécessaires. Ces valeurs sont généralement établies soit par des mesures, soit par des calculs à l'aide d'un modèle. Toutefois, il existe des preuves d'un important écart de performance énergétique (Energy Performance Gap, EPG) des bâtiments, défini comme la différence entre la consommation d'énergie mesurée et calculée. Il existe un large consensus dans la littérature sur le fait que les bâtiments à faible rendement thermique (faible cote énergétique) ont tendance à consommer moins d'énergie que prévu. A l'inverse, les bâtiments à haut rendement thermique (cote énergétique élevée) ont tendance à consommer plus que prévu.

Plusieurs projets européens ont eu pour objectif de surveiller la performance réelle des bâtiments et de réduire l'EPG, notamment EPISCOPE (Allemagne), TRIME (Pays-Bas), TRIBUTE (Irlande), HIT2GAP (France), UserTEC (Danemark). Toutefois, ces projets se limitent aux pays de l'UE et excluent la Suisse. De plus, il n'est pas clair si et dans quelle mesure ces résultats peuvent être appliqués au parc immobilier suisse. GAPxPLORE, qui couvre des milliers de bâtiments, est donc l'étude la plus complète menée jusqu'à présent en Suisse et fournit des résultats statistiquement représentatifs, offrant ainsi un aperçu supplémentaire aux décideurs politiques.

Objectifs et contenu des sections

Le projet GAPxPLORE vise à évaluer l'EPG dans le parc immobilier Suisse. Il étudie la distribution de l'EPG en fonction des typologies de bâtiments (niveau de performance et âge). Des ensembles de données de grande échelle provenant de diverses sources contenant des données calculées et réelles sur la consommation d'énergie des bâtiments sont analysés. GAPxPLORE explore également le déficit d'économies d'énergie (Energy Savings Deficit, ESD), défini comme la différence entre les réductions de consommation d'énergie prévues et réalisées dans les bâtiments rénovés. L'accent est mis sur l'énergie finale consommée pour le chauffage et l'eau chaude sanitaire dans les bâtiments résidentiels.

Quatre sources de données ont été utilisées. La première est la base de données du Certificat énergétique cantonal suisse des bâtiments (CECB), qui fournit un échantillon de 50 000 bâtiments. Deuxièmement, les données de Swiss Solar Agency ont été utilisées, qui ont été collectées à partir des candidatures au Prix Solaire Suisse et concernent des bâtiments neufs et récemment rénovés qui peuvent être considérés comme des exemples des meilleures pratiques en matière de performance énergétique. Ces données comprennent des données mesurées sur la consommation d'énergie d'environ 150 bâtiments. Le troisième ensemble de données provient des bâtiments suisses Minergie. La quatrième source de données est la plateforme Energo, qui contient la consommation d'énergie mesurée de bâtiments dans toute la Suisse. Après avoir nettoyé et filtré les données (p. ex. élimination des valeurs invraisemblables), seule une partie de chacun de ces ensembles de données a finalement été utilisée.

Le rapport se compose d'une section introductive suivie de six sections présentant les analyses effectuées.

- La **section 2** contient une revue de la littérature sur l'EPG en Europe et en Suisse dans le but de créer une vue d'ensemble des résultats existants pour la Suisse et de les comparer avec des pays européens similaires. Les informations concernant l'EPG dans les bâtiments suisses sont encore rares et se fondent essentiellement sur des études de cas. La compréhension du parc immobilier dans son ensemble est donc insuffisante.
- La **section 3** présente les sources de données utilisées pour l'analyse et évalue leur représentativité. Le nettoyage et le filtrage préliminaires des données sont décrits, ainsi que la taille des échantillons utilisés.
- La **section 4** étudie l'EPG du parc immobilier suisse à l'aide de la base de données CECB, ce qui permet d'obtenir des résultats statistiquement représentatifs sur la taille de l'EPG ainsi que des résultats par catégorie de bâtiment.
- La **section 5** étudie les corrélations entre les économies prévues et les économies réalisées grâce à la rénovation des bâtiments en utilisant un sous-échantillon de l'ensemble de données du CECB.
- La **section 6** étudie l'EPG dans les bâtiments à haut rendement énergétique par type de norme (Minergie, Minergie-P, Minergie-A) et par type de bâtiment. L'objectif est de comparer l'EPG des bâtiments Minergie-P par rapport à l'EPG obtenu pour d'autres labels. Pour ce faire, les ensembles de données fournis par Swiss Solar Agency, Energo et Minergie ont été utilisés.
- La **section 7** présente plusieurs études de cas sur des bâtiments Minergie tirées de la base de données Energo. L'analyse prend en compte les calculs de la phase de conception ainsi que la maintenance et l'optimisation après la mise en service des bâtiments afin d'explorer les causes de l'EPG.

Enfin, les **sections 8** et **9** présentent les limites et les conclusions.

Résultats

La revue de la littérature existante sur l'écart de performance énergétique a montré le calcul de l'EPG repose sur un certain nombre de définitions différentes et qu'un large éventail de valeurs sont rapportées. Trois types d'interprétation ont été identifiés, qui se distinguent par la façon dont la consommation calculée (pour comparaison ultérieure avec la consommation réelle) est modélisée : l'écart de performance peut ainsi être qualifié de réglementaire, statique ou dynamique. L'écart de performance réglementaire, qui compare le rendement d'un bâtiment dans des conditions nationales normalisées à la consommation d'énergie mesurée, est le type d'EPG le plus largement utilisé et il joue également un rôle important dans cette étude.

La diversité des paramètres et de la terminologie utilisée et la difficulté qui en découle de tirer des conclusions solides constituent des obstacles à la détermination finale de l'EPG. Pour ce faire, il faudrait préciser très clairement ce qui est inclus dans les valeurs de consommation qui sont comparées et quel type d'énergie est comparé (c'est-à-dire la demande en chauffage ou l'énergie finale pour la pleine utilisation du bâtiment). La littérature et la législation suisses manquent de clarté dans la mesure où le propriétaire ou l'habitant du bâtiment consomme (et paie) l'énergie finale au compteur, tandis que les labels énergétiques (CECB et Minergie) et les législations/normes correspondantes font référence à "l'énergie finale pondérée" calculée à partir de facteurs nationaux. Ces facteurs, qui sont définis collectivement par les cantons, reflètent leur politique énergétique plutôt que la performance de l'enveloppe du bâtiment ou du système de chauffage.

Les résultats du projet confirment l'existence d'un EPG pour les bâtiments résidentiels suisses, avec une médiane de -11% (c'est-à-dire que la performance du bâtiment médian est légèrement meilleure que prévu). La consommation réelle totale d'énergie finale est inférieure de 6% à ce qui avait été prévu à partir de la consommation d'énergie calculée. Cette valeur est différente de la valeur médiane de l'EPG, car le delta de consommation totale du parc immobilier est le résultat de la pondération des valeurs de l'EPG par bâtiment avec le total des surfaces de référence énergétique (Energy Reference Area, ERA) par classe de bâtiments et la consommation énergétique spécifique par mètre carré.

En outre, l'analyse des données montre une forte corrélation entre le label énergétique et l'EPG. Pour les bâtiments à faible performance labellisés G, un EPG négatif de -40% a été trouvé, tandis que pour les bâtiments plus performants portant le label B, un EPG positif de +12% a été trouvé. Ces résultats corroborent les résultats antérieurs de la littérature selon lesquels les bâtiments à haut rendement énergétique consomment un peu plus que prévu, tandis que les bâtiments à faible rendement énergétique consomment significativement moins que prévu.

Un sous-échantillon des données du CECB a ensuite été généré, comprenant des bâtiments résidentiels ayant obtenu une certification du CECB à la fois avant et après rénovation, afin d'étudier la relation entre les économies attendues et réalisées grâce aux améliorations énergétiques. Ce sous-échantillon comprenait 1172 bâtiments. Pour tous ces bâtiments, le déficit d'économies d'énergie a été calculé. Deux versions du ESD sont proposées dans cette étude : le « ESD réglementaire » (ESDr) défini en utilisant les économies théoriques (basées sur la consommation d'énergie théorique avant et après rénovation) comme économies attendues, et le « ESD anticipé » (ESDa) en utilisant les économies prévues (différence entre la consommation réelle avant rénovation et la consommation théorique après rénovation) comme économies attendues. Indépendamment de la méthode de calcul, il a été constaté qu'en dépit d'une augmentation de la surface chauffée de 7% au cours de la rénovation énergétique, la consommation finale totale d'énergie et les émissions de CO_2 à des fins thermiques ont diminué de moitié dans l'échantillon de bâtiments.

Le ESDr et le ESDa ont été calculés pour l'ensemble du sous-échantillon, ce qui donne un ESDr médian de 37,3% et un ESDa médian de 3,60%. Le résultat pour le ESDr implique que, sur la base des valeurs théoriques, seules 62,7% (100% - 37,3%) des économies escomptées sont effectivement réalisées. En utilisant les valeurs prévues (ESDa), 96,4% (100% - 3,60%) des économies attendues sont effectivement réalisées. De plus, il a été constaté que le ESDr augmente avec l'amélioration du label, ce qui signifie que les économies d'énergie réalisées grâce à une rénovation en profondeur représentent environ la moitié de celles qui ont été calculées. Le ESDa a montré la tendance inverse, diminuant avec une amélioration du label, jusqu'à ce qu'il devienne même négatif pour de profonds réaménagements (ce qui signifie que plus d'énergie est économisée que prévu).

Enfin, l'EPG a été étudié dans un échantillon de 56 bâtiments de haute performance, en se concentrant sur la différence d'EPG entre les différentes normes Minergie (Minergie, Minergie-P et Minergie-A).

Les indices Minergie ont été utilisés comme consommation théorique, représentant ainsi la consommation totale d'énergie pour tous les besoins des bâtiments (et différant de la consommation théorique définie dans les parties précédentes de l'étude, qui ne comprenait que le chauffage des locaux et l'eau chaude sanitaire).

Un EPG médian de -14% a été observé. Les résultats confirment la baisse de l'EPG pour les bâtiments Minergie-P de -12% pour les nouvelles constructions et de -18 % pour les bâtiments rénovés, et aussi pour les bâtiments Minergie-A avaient un EPG de -16% pour les nouvelles constructions et de -5.3% pour les bâtiments rénovés. Il est à noter que même si le pourcentage de EPG semble élevé, en valeur absolue, la consommation réelle ne dépasse l'objectif Minergie-A que de 8 kWh/(m^2y) dans les bâtiments neufs et de 12 kWh/(m^2y) dans les bâtiments rénovés.

En ce qui concerne les études de cas, l'EPG lié à la consommation de chaleur a présenté des variations de -44% à +93% et celui de l'électricité de -2,93% à +132%. Les principales raisons de l'EPG pour la chaleur résident dans le fait que les températures du circuit primaire de chauffage des locaux et de l'eau chaude étaient plus élevées que les températures standards et que les fenêtres étaient restées ouvertes trop longtemps, provoquant des chutes de température. Les principales raisons de l'écart de performance pour la consommation d'électricité sont les horaires incorrects des systèmes de ventilation et l'importante consommation d'énergie des appareils ménagers. Il a été constaté que l'une des plus grandes incertitudes dans l'estimation de l'EPG d'un bâtiment n'est pas la collecte de données de consommation réelle mais la détermination de la consommation théorique. Dans les études de cas qui ont été analysées, entre 44% et 76% de la consommation théorique ont été calculés avec des indices paramétriques et la consommation d'énergie restante est calculée de manière plus précise mais non homogène (par exemple, elle est parfois déterminée sur une base horaire, mensuelle ou autre). En effet, les calculs énergétiques effectués lors de la phase de conception d'un bâtiment n'ont pas pour objectif de prévoir la consommation totale finale mais d'évaluer l'efficacité des principaux choix de conception et leur conformité aux exigences énergétiques en respectant les limites établies par des normes ou lois standardisées.

Conclusions

GAPxPLORE a confirmé l'existence d'un EPG dans le secteur résidentiel suisse, les bâtiments à faible performance thermique ayant tendance à consommer moins que prévu (EPG négatif) et les bâtiments à haute performance thermique ayant tendance à consommer légèrement plus que prévu (EPG positif). Les valeurs observées sont inférieures à celles rapportées dans les études de cas existantes en Suisse, en partie parce qu'il s'agit de la première évaluation de grande échelle (plutôt que de se concentrer sur un petit nombre de bâtiments à haute efficacité). Cela peut également être dû au fait que le propriétaire d'un bâtiment faisant une demande de certificat accorde plus d'attention à l'efficacité énergétique que le propriétaire moyen. Il est important de souligner que les valeurs diverses de l'EPG relevées pour les cotes faibles et élevées impliquent des niveaux variables de consommation finale d'énergie, puisqu'un point de pourcentage représente des valeurs de consommation d'énergie très différentes en termes de kWh/(m^2y) pour la cote faible comparativement à la cote élevée. C'est la raison pour laquelle il convient d'interpréter avec prudence les valeurs en pourcentage de l'EPG pour différents labels énergétiques et de se concentrer plutôt sur l'impact en termes de consommation finale totale d'énergie.

Les résultats en termes de déficit d'économies d'énergie pour les bâtiments rénovés suggèrent que le ESD réglementaire (ESDr) n'est pas un bon indicateur de la qualité d'une rénovation énergétique, car la majeure partie du déficit est due à une surestimation de la consommation du bâtiment avant sa rénovation. Par conséquent, le ESDr reflète l'erreur dans le calcul des économies théoriques plutôt que la qualité de la rénovation elle-même. Inversement, le déficit d'économies d'énergie prévu (ESDa) s'avère être un indicateur nettement plus fiable pour juger du succès d'une rénovation compte tenu de la faible erreur en termes absolus (seulement 3,60%). Le ESDa présente l'avantage supplémentaire que des écarts importants entre les économies prévues et les économies réelles pourraient être utilisés pour identifier les défaillances du système ou les défaillances opérationnelles (c.-à-d. que si le bâtiment ne fonctionne pas comme prévu, cela est probablement lié à un problème pratique plutôt qu'à une erreur de calcul). Enfin, la faible valeur du ESDa qui a été constatée suggère que la qualité globale des rénovations énergétiques réalisées dans ce sous-échantillon est élevée, ce qui indique, entre autres, que la qualité du travail réalisé n'est pas un problème majeur en Suisse. En outre, cette analyse rassure sur le fait que les objectifs d'économies sont souvent atteints, ce que les décideurs politiques et les investisseurs pourraient également trouver encourageant tout en gardant à l'esprit que cette analyse était basée sur un sous-ensemble relativement restreint des données du CECB.

L'analyse des bâtiments Minergie, qui résulte en un EPG négatif de -14% (c'est-à-dire que le bâtiment médian consomme légèrement moins que prévu), vient étayer l'hypothèse initiale selon laquelle les bâtiments les plus robustes en termes d'EPG (un EPG de -6,2 % a été trouvé pour les bâtiments portant le label A de l'échantillon CECB pour le chauffage et l'eau chaude sanitaire). Toutefois, cette constatation pourrait être en partie une conséquence du petit échantillon utilisé (56 bâtiments) et de ses caractéristiques.

En conclusion, le constat pour l'ensemble du parc immobilier résidentiel suisse, selon lequel la consommation réelle totale d'énergie finale est inférieure de 6% aux prévisions, est rassurant mais contrasté par rapport à certaines études antérieures s'appuyant sur des études de cas en Suisse. Nos résultats se fondent sur l'échantillon du CECB et des recherches supplémentaires seraient nécessaires pour comprendre si les bâtiments inclus dans cet échantillon présentent de meilleures performances que la moyenne en Suisse. De même, l'EPG global limité que l'on trouve pour les bâtiments à haut rendement est rassurant, les bâtiments Minergie-P, Minergie-A affichant même des performances supérieures aux valeurs théoriques. Compte tenu de l'origine des données (Prix Solaire Suisse) et de la taille réduite de l'échantillon, ces résultats ne doivent pas être généralisés bien qu'ils montrent que des niveaux d'efficacité énergétique élevés peuvent être atteints de manière réaliste.

Zusammenfassung

Einleitung

Gebäude machen 40% des gesamten Endenergieverbrauchs in der Schweiz aus, während 70% der im Jahr 2016 im Wohnbereich eingesetzten Endenergie auf die Raumheizung entfielen. Um diesen Verbrauch zu senken, setzt der Bundesrat im Einklang mit den energiepolitischen Massnahmen der EU seit 2011 ihre Energiestrategie 2050 (ES-2050) um. Diese basiert auf drei strategischen Zielen: Steigerung der Energieeffizienz, erhöhte Nutzung erneuerbarer Energien und Ausstieg aus der Kernenergie. Für Wohngebäude bedeutet dies, dass gemäss der "Neuen Energiepolitik" der Endenergiebedarf bis 2050 um 46% und die CO_2-Emissionen um 77% reduziert werden müssen. Für den Erfolg der Energie- und Klimapolitik ist es daher entscheidend, das Energieeinsparpotenzial des Gebäudebestandes genau abzuschätzen. Zu diesem Zweck werden zuverlässige Werte für den Energiebedarf von bestehenden und energetisch sanierten Gebäuden benötigt. Diese Werte werden in der Regel entweder durch Messung oder durch Modellberechnungen ermittelt. Es ist allerdings bekannt, dass der gemessene und der berechnete Energieverbrauch in Gebäuden auseinanderklaffen können. Im Englischen wird diese Differenz als *Energy Performance Gap* (EPG) bezeichnet (dieser eingebürgerte Ausdruck wird auch in dieser deutschen Zusammenfassung im Folgenden weiter verwendet). In der Literatur herrscht weitgehend Einigkeit darüber, dass Gebäude mit schlechter Dämmung (niedrige Energielabel) tendenziell weniger verbrauchen als ursprünglich erwartet, d.h. weniger als unter standardisierten Bedingungen (gemäss nationalen Normen) berechnet. Umgekehrt verbrauchen gut gedämmte Gebäude (gute Energielabel) mehr Energie als berechnet.

In der Vergangenheit haben sich mehrere EU-Projekte damit beschäftigt, die reale Energieeffizienz von Gebäuden zu ermitteln und den EPG zu reduzieren, unter anderem die Projekte EPISCOPE (Deutschland), TRIME (Niederlande), TRIBUTE (Irland), HIT2GAP (Frankreich) und UserTEC (Dänemark). Diese Projekte sind jedoch auf EU-Länder beschränkt und schliessen damit die Schweiz aus. Zudem ist unklar, ob und inwieweit die Erkenntnisse auf den Schweizer Gebäudebestand übertragbar sind. Unser Projekt GAPxPLORE, welches Tausende von Gebäuden untersucht, ist die bisher umfassendste Studie in der Schweiz und hat als Ziel, statistisch repräsentative Ergebnisse zu liefern, die wertvolle Einblicke für politische Entscheidungsträger und andere Interessensgruppen ermöglichen.

Ziele und Gegenstand

Das Projekt GAPxPLORE zielt darauf ab, den EPG im Schweizer Gebäudebestand zu ermitteln. Es wird untersucht, wie sich der EPG auf die Gebäudetypologien (Dämmniveau und Alter) verteilt. Es werden grosse Datensätze aus verschiedenen Quellen analysiert, um den berechneten mit dem tatsächlichen Energieverbrauch zu vergleichen. GAPxPLORE untersucht auch die *Energieeinsparlücke* (englisch: Energy Savings Deficit, ESD), den wir für energetische Sanierungen als Differenz zwischen erwarteter (berechneter) und tatsächlich erzielter Energieeinsparung definieren. Der Fokus liegt hierbei auf dem Endenergiebedarf für Heizung und Warmwasserbereitung in Wohngebäuden.

Es wurden vier Datenquellen genutzt: Zum einen handelt es sich um die Datenbank des Gebäudeenergieausweises der Kantone (GEAK; *Cantonal Energy Certificate for Buildings*, CECB), die insgesamt 50'000 Gebäude umfasst. Zweitens wurden Daten der Solar Agentur Schweiz verwendet, die aus Bewerbungen um den Schweizer Solarpreis stammen und sowohl neue als auch energetisch sanierte Gebäude beinhalten, die als Best-Practice-Beispiele in Bezug auf ihre Energieeffizienz angesehen werden können. Diese Daten umfassen gemessene Energieverbrauchsdaten von rund 150 Gebäuden. Der dritte Datensatz beinhaltet 45'000 Schweizer Minergie-Gebäude. Der vierte Datensatz stammt aus der Energo-Plattform mit gemessenen Energieverbrauchsdaten von mehr als 5'000 Gebäuden. Nur ein Teil dieser Datensätze wurde nach Auswahl und Aufbereitung der Daten (z.B. Entfernung unplausibler Werte) letztendlich verwendet.

Dieser Bericht besteht aus einem einleitenden Kapitel, gefolgt von sechs Kapiteln, in welchen die einzelnen Auswertungen beschrieben werden.

- In **Kapitel 2** wird eine Literaturrecherche zum EPG in Europa und der Schweiz vorgestellt, mit dem Ziel, einen Überblick über die für die Schweiz vorliegenden Ergebnisse zu bieten und mit Ergebnissen aus EU-Ländern zu vergleichen. Bislang gibt es nur recht wenige Informationen über den EPG in Schweizer Gebäuden, und die vorliegenden Erkenntnisse basieren hauptsächlich auf Fallstudien; das Verständnis für den Gebäudebestand als Ganzes ist unvollständig.
- **Kapitel 3** erläutert die für die Analyse verwendeten Datenquellen und bewertet deren Repräsentativität. Die Aufbereitung der Daten sowie die verwendeten Stichprobengrössen werden beschrieben.
- **Kapitel 4** untersucht mit Hilfe der GEAK-Datenbank den EPG im schweizerischen Gebäudebestand. Daraus können statistisch repräsentative Ergebnisse zum Ausmass des EPG abgeleitet werden sowie Ergebnisse für die einzelnen Gebäudekategorien.
- **Kapitel 5** beinhaltet den Vergleich zwischen berechneter und tatsächlich erzielter Energieeinsparung durch energetische Sanierung basierend auf der Analyse eines Teiles des GEAK-Datensatzes.
- **Kapitel 6** untersucht den EPG in hocheffizienten Gebäuden für verschiedene Subtypen des Minergie-Standards (Minergie, Minergie-P, Minergie-A) und nach Gebäudeart. Ein wichtiges Ziel ist es dabei zu verstehen, wie der EPG von Minergie-P-Gebäuden im Vergleich zu anderen Labels abschneidet. Hierfür werden die von der Solaragentur, Energo und Minergie bereitgestellten Datensätze verwendet.
- **Kapitel 7** präsentiert Fallstudien zu Minergie-Gebäuden aus der Energo-Datenbank. Die Analyse umfasst die Planungsphase, den Betrieb sowie Wartung und Optimierung zur Identifizierung der Ursachen des EPG.

In **Kapitel 8 en 9** werden schliesslich die Schlussfolgerungen und der Ausblick präsentiert.

Resultate

Die Literaturrecherche zum EPG hat ergeben, dass eine Reihe unterschiedlicher Definitionen für die Berechnung des EPG verwendet werden und dass die ermittelten Werte eine grosse Bandbreite aufweisen. Es lassen sich drei Definitionen differenzieren, die sich darin unterscheiden, wie der berechnete Verbrauch (zum späteren Vergleich mit dem tatsächlichen Verbrauch) modelliert wird: ein regulatorischer, statischer und dynamischer EPG. Am weitesten verbreitet is der regulatorische EPG, der den Unterschied zwischen dem Energiebedarf eines Gebäudes unter standardisierten

Bedingungen (gemäss nationalen Normen) mit dem gemessenen Energiebedarf wiedergibt und auch in dieser Studie eine zentrale Rolle spielt.

Diese Vielfalt bezüglich der verwendeten Indikatoren und der Terminologie und die sich daraus ergebende Herausforderung, fundierte Schlussfolgerungen zu ziehen, stellen Hindernisse für das Schliessen des EPG dar. Dazu müsste die Abgrenzung der verglichenen Verbrauchswerte inklusive der Energieverbrauchskategorie immer eindeutig definiert sein (z.B. nur Wärmebedarf bzw. Endenergie für alle im Gebäude erbrachten Energiedienstleistungen). In der schweizerischen Literatur und Gesetzgebung gibt es gewisse Unklarheiten (oder zumindest ein Potenzial für Missverständnisse), denn der Gebäudeeigentümer oder Bewohner verbraucht (und bezahlt) die vom Zähler angezeigte Endenergie, während sich die Energielabels (GEAK und Minergie) und die damit verbundenen Gesetze/Normen auf die mit nationalen Faktoren "gewichtete Endenergie" beziehen. Diese Faktoren werden von den Kantonen gemeinsam definiert und spiegeln eher deren Energiepolitik wider als das Dämmniveau der Gebäudehülle oder die Effizienz der Heizungsanlage.

Unsere Ergebnisse bestätigen die Existenz des EPG für Schweizer Wohngebäude mit einem Median von -11% (d.h. der Median der Gebäude liegt etwas unter dem berechneten Energiewert). Für den gesamten Wohngebäudebestand ist der tatsächliche Endenergiebedarf 6% niedriger als der berechnete Bedarf. Diese Abweichung (-6%) unterscheidet sich vom Median-EPG (-11%), da sich das Gesamtverbrauchsdelta über den Gebäudebestand aus der Gewichtung der EPG-Werte pro Gebäude mit den Gesamtwohnflächen nach Gebäudeklasse und dem spezifischen Energieverbrauch pro Quadratmeter ergibt.

Darüber hinaus zeigt die Datenanalyse eine starke Korrelation zwischen dem spezifischen Energiebedarf und dem EPG. Für relativ ineffiziente Gebäude mit G-Label wurde eine negativer EPG von -40% ermittelt, während sich für die effizienten Gebäude mit B-Label ein positiver EPG von +12% ergibt. Diese Ergebnisse bestätigen die Erkenntnisse aus der Literaturrecherche, wonach effiziente Gebäude etwas mehr Energie verbrauchen als ursprünglich berechnet wurde, während ineffiziente Gebäude deutlich weniger verbrauchen als berechnet.

Anschliessend wurde unter Nutzung eines Teiles des GEAK-Datensatzes der Zusammenhang zwischen der mit der energetischen Sanierung verbundenen, erwarteten Energieeinsparung und der tatsächlich erzielten Einsparung untersucht. Der Datensatz besteht aus Wohngebäuden, die sowohl vor als auch nach der Renovierung über eine GEAK-Zertifizierung verfügten. Dieser Datensatz umfasst 1172 Gebäude. Für alle diese Gebäude wurde die Energieeinsparlücke (EEL; englisch: Energy Savings Deficit, ESD) berechnet. In dieser Studie wird die Energieeinsparlücke in zwei Versionen berechnet: als regulatorische EEL (EELr) unter Verwendung der theoretischen Einsparungen (d.h. basierend auf dem theoretischen Energieverbrauch vor und nach der energetischen Sanierung), und als antizipierte EEL (EELa), die sich als Differenz zwischen dem tatsächlichen Verbrauch vor der energetischen Sanierung und dem theoretischen Verbrauch nach der Sanierung ergibt. Unabhängig von der Berechnungsmethode wurde festgestellt, dass die energetische Sanierung trotz der Erhöhung der beheizten Fläche um 7% die Halbierung des Endenergieverbrauch für Heizzwecke und der CO_2-Emissionen für die in diesem Datensatz enthaltenen Gebäude ermöglicht hat.

Die Berechnung der Energieeffizienzlücke (EEL) für die 1172 Gebäude ergibt Medianwerte für EELr und EELa von 37,3% bzw. 3,60%. Das EELr-Wert beinhaltet, dass basierend auf den theoretischen Werten nur 62,7% (100% - 37,3%) der erwarteten Einsparungen tatsächlich erreicht werden. Stattdessen besagt der EELa-Wert, dass 96,4% (100% - 3,60%) der erwarteten Einsparungen tatsächlich erreicht werden. Darüber hinaus wurde festgestellt, dass der EELr-Wert für bessere Labels zunimmt; konkret bedeutet dies, dass die durch energetische Sanierungen tatsächlich erzielten Energieeinsparungen etwa nur der Hälfte der berechneten Einsparungen entsprechen. Für den EELa ergab sich ein gegenteiliger Trend: die Energieeffizienzlücke nahm für bessere Labels ab, bis sie für eine sehr tiefgreifende energetische Sanierung sogar negativ wurde (was bedeutet, dass mehr Energie eingespart wird als ursprünglich berechnet wurde).

Schliesslich wurde der EPG für eine Stichprobe von 56 hocheffizienten Gebäuden untersucht, wobei das Hauptaugenmerk auf dem Unterschied des EPG zwischen den verschiedenen Minergie-Standards (Minergie, Minergie-P und Minergie-A) lag. Die Minergie-Indexe dienten als Grundlage für den berechneten Gesamtenergieverbrauch für alle in dem Gebäude erbrachten Energiedienstleistungen (im Gegensatz zu den vorangehenden Vergleichen, die sich ausschliesslich auf Raumwärme und Warmwasser bezogen). Für den Median des EPG ergab sich ein Wert von -14%. Die Ergebnisse bestätigen das bessere Abschneiden der Minergie-P-Gebäude mit einem EPG von -12% für Neubauten und -18% für energetische Sanierungen sowie von Minergie-A-Gebäuden mit einem EPG von -16% für Neubauten und -5,3% für energetische Sanierungen. Wenngleich die Prozentwerte bemerkenswert erscheinen, liegt der tatsächliche Verbrauch in absoluten Einheiten bei Minergie-P-Gebäude nur um 4 kWh/m^2/Jahr unter dem Zielwert und für Minergie-A nur um 6 kWh/m^2/Jahr unter dem Zielwert (alle Werte beziehen sich auf den Gesamtenergiebedarf der Gebäude).

Bei den in Kapitel 7 untersuchten Fallstudien lag der EPG für Wärme zwischen -44% und +93% und für Strom zwischen -2,9% und +132%. Die Hauptgründe für den EPG bei der Wärmebereitstellung liegen darin, dass i) die Primärkreislauftemperaturen für Raumheizung und Warmwasser höher waren als die Standardtemperaturen und dass ii) die Fenster zu lange offenstanden, was zu Temperaturabfällen führte. Die Hauptgründe für den EPG bei Strom sind die fehlerhafte Zeitregelung der Lüftungsanlagen und der hohe Energieverbrauch der Haushaltsgeräte. Es wurde festgestellt, dass eine der grössten Unsicherheiten bei der Bestimmung des EPG eines Gebäudes nicht die Erhebung von tatsächlichen Verbrauchsdaten, sondern die Bestimmung des theoretischen Verbrauchs ist. In den analysierten Fallstudien wurden zwischen 44% und 76% des theoretischen Verbrauchs parametrisch ermittelt. Der verbleibende Energieverbrauch wurde präziser ermittelt, wobei allerdings methodisch unterschiedliche Ansätze verfolgt wurden (z.B. manchmal auf Stunden- oder Monatsbasis oder in anderen Zeitschrittens). Tatsächlich hat der während der Entwurfsphase eines Gebäudes ermittelte theoretische Energiebedarf nicht das Ziel, den tatsächlichen Endenergieverbrauch vorherzusagen, sondern liefert vielmehr eine Entscheidungsgrundlage für die wichtigsten bautechnischen Optionen mit dem Ziel der Einhaltung des Energiebedarfs gemäss standardisierter Bedingungen bzw. im Einklang mit gesetzlich festgelegten Grenzwerten.

Schlussfolgerungen

Im GAPxPLORE-Projekt wurde die Existenz eines EPG (Energy Performance Gap) im Schweizer Wohnungsbereich bestätigt, wobei Gebäude mit geringer Dämmung tendenziell weniger verbrauchen als vorhergesagt (negativer EPG), während Gebäude mit guter Dämmung tendenziell etwas mehr als berechnet verbrauchen (positiver EPG). Die Abweichungen sind kleiner als die in früheren Fallstudien für die Schweiz ermittelten Werte. Dies mag unter anderem daran liegen, dass es sich um die erste Untersuchung für den gesamten Wohngebäudebestand handelt (und nicht um eine geringe Anzahl von Fallbeispielen hocheffizienter Gebäuden). Ausserdem schenken Gebäudeeigentümer, die ein Energielabel nach GEAK beantragen, möglicherweise der Energieeffizienz mehr Aufmerksamkeit als der durchschnittliche Eigentümer. Schliesslich sind die für diese Analyse verwendeten GEAK-Daten möglicherweise aus anderen Gründen (z.B. kantonale Verteilung, Datenaufbereitung etc.) nicht vollständig repräsentativ für den Schweizer Gebäudebestand.

Es ist wichtig zu betonen, dass die diversen EPG-Prozentsätze sehr unterschiedlichen Energieverbrauchswerten entsprechen, je nachdem ob es sich um Gebäude mit hoher oder niedriger Energieeffizienz handelt; denn je nach Effizienz des Gebäudes kann ein Prozentpunkt sehr unterschiedlichen Energieverbrauchswerten, ausgedrückt in kWh/m^2/Jahr, entsprechen. Aus diesem Grund ist bei der Interpretation des EPG in Prozentwerten für verschiedene Energielabels Vorsicht geboten, und stattdessen sollte das Hauptaugenmerk auf den Konsequenzen für den Endenergieverbrauchs liegen.

Die Ergebnisse zur Energieeffizienzlücke (EEL) für energetisch sanierte Gebäude deuten darauf hin, dass die regulatorische EEL (EELr) kein guter Indikator für die Qualität einer energetischen Sanierung ist, da der grösste Teil der Effizienzlücke auf eine Überschätzung des Verbrauchs des Gebäudes vor der Sanierung zurückzuführen ist. Daher spiegelt der EELr-Wert den Fehler in der Berechnung der theoretischen Einsparungen wider und nicht die Qualität der energetischen Sanierung selbst. Umgekehrt erweist sich der antizipierte EEL (EELa) als deutlich zuverlässigerer Indikator für die Beurteilung des Erfolgs einer energetischen Sanierung; dies wird aus dem deutlich geringeren absoluten Fehler (von nur 3,6%) deutlich. Der EELa-Wert ermöglicht es ausserdem, signifikante Abweichungen zwischen erwarteten und tatsächlichen Einsparungen zu identifizieren, die dann als Hinweis auf System- oder Betriebsstörungen dienen können (bei Unregelmässigkeiten im Energiebedarf eines Gebäude ist es wahrscheinlicher, dass dies mit einem praktischen Problem zusammenhängt als mit einem Fehler in der Berechnung). Schliesslich deutet ein kleiner EELa-Wert darauf hin, dass die Qualität der energetischen Sanierung für die in diesem Datensatz repräsentierten Gebäude hoch ist, was unter anderem ein Hinweis dafür ist, dass die bautechnische Ausführung in der Schweiz kein grösseres Problem darstellt. Diese Analyse bestätigt zudem, dass anspruchsvolle Energieeinsparziele im Gebäudebestand oftmals erreicht werden. Dies könnte auch für Politiker und Investoren motivierend wirken, wobei zu bedenken ist, dass diese Auswertung auf einer relativ kleinen Teilmenge des GEAK-Datensatzes beruht.

Für die Analyse der Minergie-Gebäude ergibt sich ein negativer EPG von -14% (d.h. das Median-Gebäude verbraucht etwas weniger als ein Gebäude unter standardisierten Bedingungen). Dies bestätigt die Hypothese, wonach die effizientesten Gebäude weniger anfällig für den EPG sind (für Gebäude mit einem A-Label ergibt sich aus dem GEAK-Datensatz ein EPG für Raumwärme und Warmwasser von -6,2%). Dieser Befund könnte jedoch teilweise eine Folge der kleinen Stichprobe (56 Gebäude) und ihrer spezifischen Eigenschaften sein. Diese Gebäude wurden nämlich alle in einem Wettbewerb ausgewählt, in dem die energetisch überzeugendsten Objekte prämiert wurden. Dies erklärt, warum der Energieverbrauch dieser Gebäude die in den Normen vorgegebenen Werte eher übertreffen.

Zusammenfassend ist die Erkenntnis ermutigend, wonach der tatsächliche Endenergieverbrauch des gesamten schweizerischen Wohngebäudebestandes um 6% niedriger ist als der berechnete. Das Resultat steht aber im Gegensatz zu einigen Untersuchungen, die sich auf Fallstudien in der Schweiz stützen. Unsere Ergebnisse basieren auf GEAK-Daten, und weitere Untersuchungen wären erforderlich, um zu verstehen, ob die in diesem Datensatz enthaltenen Gebäude besser abschneiden als der schweizerische Durchschnitt. Ebenso stimmt der eher kleine EPG, der für hocheffiziente Gebäude ermittelt wurde, optimistisch, wobei Minergie-P und Minergie-A-Gebäude sogar die theoretischen Werte übertreffen. Angesichts der Herkunft der Daten (Schweizer Solarpreis) und des kleineren Stichprobenumfangs sollten diese Ergebnisse allerdings nicht verallgemeinert werden. Sie zeigen aber dennoch, dass Gebäude mit bemerkenswert hoher Energieeffizienz tatsächlich realisierbar sind.

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List of Acronyms

CECB	Swiss Cantonal Energy Certificate for Buildings
DHW	domestic hot water
EnDK	Conference of Cantonal Energy Directors
EPBD	Energy Performance of Buildings Directive
EPG	Energy Performance Gap
ERA	energy reference area
ES-2050	Swiss Energy Strategy 2050
ESD	Energy Savings Deficit
EU	European Union
FSO	Swiss Federal Statistical Office
MFH	multi-family house
MoPEC	Model of the cantons' energy regulations
NEP	New Energy Policy
SFH	single family house
SH	space heating
SIA	Swiss Society of Engineers and Architects

1 Introduction

1.1 Background

Buildings are responsible for 40% of the total final energy consumption in Switzerland and 70% of the final energy used in 2016 in the residential sector is related to space heating (SFOE, 2017). 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, fabric, and heating systems on the energy performance. An important step forward was the introduction of the European Energy Performance of Buildings Directive, in which, among several measures, all the Member States have been obliged to adopt energy performance certificate for buildings that are constructed, sold or rented out to a new tenant, to ensure that performance fulfils the national minimum energy performance requirements (The European Parliament and the Council of the EU, 2003).

In practice, the performance certificate reports the expected energy consumption if the building is used in compliance with the standards. The reliability of these performance certificates, as well as of other private labelling systems such as Breeam (BRE Global, 2015) or Minergie (Minergie, 2010), and more generally of any building calculation-based performance evaluation, becomes critical for achieving future energy targets (IPCC, 2018), as the objectives are settled based on these expected performance levels. This consequently leads to the question whether the calculated energy performance levels are realistic.

Previous research identified significant limits to progress in energy efficiency improvement, referring to this problem of the difference between measured and calculated energy consumption of a building (Cayre et al., 2011; Galvin, 2014; Gram-Hanssen and Georg, 2017; Grossmann et al., 2016; Ménard, 2016; Sunikka-Blank and Galvin, 2012; Van den Brom et al., 2017). This deviation is named Energy Performance Gap (EPG), and typically concerns the difference between predicted performance of the design intent with observed performance of the realized building over the time (de Wilde, 2014). Although there are various approaches to analyse the EPG, the definition of the difference in consumption as a proportion of the theoretical consumption for a given building is broadly accepted (Galvin, 2014):

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

Equation 1

Although it is difficult to establish direct relations between the magnitude of the EPG and the local national standards, a common pattern has been found on how the EPG depends on a building's thermal performance: there is a broad agreement in the literature that buildings with poor thermal performance (low energy rating) tend to consume less than predicted. Vice versa, buildings with high thermal performance (high energy rating) tend to consume more than predicted (Merzkirch et al., 2014; Ramallo-González, 2013; Risholt and Berker, 2013; Sharpe and Shearer, 2013). For example, Majcen (2016) found that very efficient buildings in the Netherlands have a positive EPG (+20%, consuming more than expected) while very inefficient buildings have a negative EPG (-50%, i.e. actual consumption was half the theoretical consumption). A similar result was found by Cayre *et al.* (2011) for France, by Hens, Parijs and Deurinck (2010) for Belgium, by Sunikka-Blank and Galvin (2012) for Germany and by Kelly (2011) for UK. Multiple analyses have, however, revealed that the implementation of energy performance certificates differs across countries, and consequently the findings from previous studies cannot be assumed to apply to any other country (Andaloro et al., 2010; Delghust et al., 2015).

It is currently unclear whether and to what extent these findings can be applied to the Swiss building stock, as research so far has focused on a few case studies or small samples (Hoffmann and Geissler, 2017a; Lehmann et al., 2017; Thaler and Kellenberger, 2017; Wyss and Hässig, 2016). The largest Swiss research study analysed 214 buildings (Reimann et al., 2016), including only newly built dwellings and offices, and is therefore not representative of the entire building stock.

1.2 The GAPxPLORE project

The objective of the GAPxPLORE project was to study the performance gap in the Swiss building stock. In addition to a study of the literature, large datasets from multiple sources were used containing real energy consumption data as well as design demand data of existing, new, and renovated buildings. GAPxPLORE suggests to study the Energy Performance Gap, as well as the Energy Savings Deficit (ESD, the difference between expected and achieved energy reductions in renovated buildings). The primary focus lies on the energy consumed for heating and domestic hot water, however, other aspects such as heat production and electricity use of appliances are also investigated.

GAPxPLORE responds to the first topic of the research program “Energy in Buildings” (Office federal de l’énergie, 2012), i.e. energy retrofit and the performance gap (“Bauerneuerung und Performance Gap”). This work addresses item 3 & 4 of the call text, i.e. the preparation of a comprehensive literature analysis as well as the collection of original data, their analysis and interpretation, thereby covering both renovated and new buildings.

The GAPxPLORE study, covering 50 000 building energy certificates, is the most comprehensive analysis so far conducted in Switzerland and comparable to other large scale studies in Europe (e.g. 200 000 buildings in the Netherlands (Majcen et al., 2013) and 140 000 buildings in Germany (Schröder et al., 2014)). It provides statistically significant results on the residential buildings’ performance which can offer valuable new insights for policy makers, energy utilities, local authorities, building owners and researchers.

The GAPxPLORE study consists of five tasks. The first task is an examination of the state of the art through a literature review and the preparation of the datasets for the use in this project. Tasks 2 and 3 make use of the Cantonal Energy Certificate for Buildings dataset to analyse the building stock, while Task 4 is based on the data for new and high-performance buildings. The objective of Task 5 is to explore opportunities for in-depth analyses of the factors underlying the performance gap; this will serve as basis for an expected continuation of the proposed study in cooperation with an additional partner.

Similar to existing performance gap studies in other countries, the focus of GAPxPLORE was final energy consumption for heating and domestic hot water. The types of building considered were mainly residential - single family house (SFH) and multi-family house (MFH) - with a small number of offices studied in Task 5. Task 2 and 3 also considered the type of heat source of the building (gas, oil, heat pump, etc), as this is relevant to the emissions impact of buildings (notably those intended to be highly ecological).

The report is divided into eight sections which cover the datasets and the project Tasks. Section 2 gives a comprehensive literature review on the EPG in Europe and Switzerland. Section 3 presents the data sources used for the analysis. The results for the EPG in the Swiss building stock and in energy retrofitted building are presented and discussed in sections 4 and 5. Section 6 reports the analysis of the EPG in high efficiency buildings and section 7 shows different case studies analysed in detail. Finally, limitations and conclusions are drawn in section 8 and 9.

1.3 Background on the energy regulation for buildings in Switzerland

Parallel to the development of the new objectives in EU energy policy, the Swiss Federal Council has been developing and implementing the Swiss Energy Strategy 2050 (ES-2050) since 2011 (Swiss Federal Office of Energy, 2018). The ES-2050 is based on three strategic objectives: increasing energy efficiency, increasing the use of renewable energy, and withdrawing from nuclear energy. For residential buildings, this translates for the final energy consumption to be reduced by 46% and CO_2 emissions by 77% compared to today levels according to the so-called “New Energy Policy” (Prognos, 2012).

However, in accordance with Art. 89 para. 4 of the Swiss Federal Constitution, measures concerning energy consumption in buildings are primarily the responsibility of the cantons. The cantons are responsible for enacting the legislation in the area of energy consumption in buildings, while the federal government has only subsidiary competence. As a result, the federal government does not have authority to directly implement the national energy strategy for buildings. Nevertheless, in order to support and help the cantons to achieve their energy targets the Conference of Cantonal Energy Directors (EnDK, Conférences des directeurs cantonaux de l'énergie) created the Model of the Cantons' Energy Regulations (MoPEC, Modèle de prescriptions énergétiques des cantons). This is a set of energy regulations drawn up jointly by the cantons, that specifies technical requirements and new minimum energy performance levels based on national norms.

The MoPEC is a "common denominator " for the cantons in which all stakeholders have participated, thus benefiting from a broad consensus. At the same time, it is the result of the sum of experience gained in the design processes. The modular structure leaves the cantons some room for manoeuvre, so that they can apply it taking into account their own particularities. This does result in variations in approaches across Switzerland.

The MoPEC pursues the following objectives:

- Issue regulations only if they have a significant impact on the energy consumption.
- Prescribe targets rather than procedures.
- Develop applicable and reliable requirements.
- Define measurable and quantified legal requirements.

On January 9, 2015, EnDK's plenary assembly released the MoPEC 2014 (fourth edition since its creation; Conferenza Cantonale dei Direttori dell’Energia CDE, 2014) for the attention of the cantons in order to be implanted in the different regulations. The objective set by EnDK in its action plan is for the cantons to adapt their energy laws by 2018 so that the new regulations can enter into force throughout Switzerland by 2020.

The core of the MoPEC 2014 is the "*basic module*" that contains the minimum requirements that heated or cooled buildings must meet across Switzerland. These requirements relate to the building envelope and the systems (heating, ventilation, air conditioning, lighting, hot water, building automation).

The targets are generally given in terms of "weighted final energy consumption", which is different from both final and primary energy consumption. The national values for the weighting factors are given in Table 1. These factors are defined collectively by the cantons and reflect the energy policies of each canton and of the Confederation (EnDK, 2016). The intention is to promote the energy sources preferred by the cantons, by penalising fossil fuels and promoting renewable energy (e.g. the national factor for Photovoltaic (PV) equal to 0). Therefore, these factors largely reflect policies and political will, rather than having physical basis.

*Table 1: National weighting factors for evaluating final energy. The primary energy factors from KBOB (2016) are reported for comparison. *The value for district heating varies depending on the energy source of the district heat network.*

Fuel	National factor (g)	Primary factor
Electricity	2	2.97
Natural gas	1	1.15
Oil	1	1.24
District Heating*	0.4 – 1.0	0.81
Biomass	0.5	1.14
Sun (PV)	0	1.55

It is important to highlight that the national factors are different from the primary energy factors used to define the primary energy consumption. This can be seen when comparing them with the primary factors (Table 1). The primary energy factors are defined using a Life Cycle Analysis (LCA) to determine the resources used to produce a kWh of a certain energy carrier. Therefore, while final and primary energy consumption values can be readily compared within Switzerland and internationally (as the method to calculate these factors is standardised across countries), it is more complicated to compare a unit of weighted final energy as the national factors are mainly political and not physical parameters.

The weighted final energy consumption for heating, domestic hot water production, ventilation and air conditioning is determined by dividing the heating demand for heating and domestic hot water by the efficiency of the selected heat generator, then multiplying the result by the national weighting factor (g) of the energy carrier used (Table 1). The result is added to the final energy consumption for ventilation and air conditioning, multiplied by the electricity weighting factor (g).

In the context of this project, the limits defined by the MoPEC for the weighted final energy for heating, domestic hot water, ventilation and air conditioning are central, and present in Table 2.

Table 2: Limit values for the weighted final energy for heating, hot water and ventilation according to the MoPEC 2014.

	MoPEC	
Building Type	**New construction [kWh/m^2y]**	**Retrofit [kWh/m^2y]**
MFH	35	60
SFH	35	60
Offices	40	55
Schools	35	55

Among the suggestions given within the MoPEC for building owners who want to renovate the thermal insulation of the building and/or the technical systems for heating and hot water, is the adoption of the Swiss Cantonal Energy Certificate for Buildings (CECB; SIA (2016a)). The CECB reports primarily information on the building envelope and its overall energy efficiency independently of the users. It also informs the owner of the first measures that can be applied to optimise its own consumption. This applies both to existing and new buildings. The calculated performance is rated using energy labels A to G (very efficient to very inefficient). Currently, there is no national obligation to apply the CECB for all new or renovated buildings as it falls under the authority of each canton (Office federal de l'énergie, 2018). However, an increasing number of cantons are making it compulsory to issue this certificate when real estate is for sale, in order to be eligible for subsidies for refurbishment measures, or for new buildings (Office federal de l'énergie, 2018).

The CECB delivers two ratings, one considers only the building envelope (walls, roof, windows, etc) while the second considers the overall energy efficiency including heating system, domestic hot water, and other loads (e.g. appliances). These ratings are obtained using the index of the normalised primary energy, that is calculated in function of a reference index representing a building with standard heating and electricity consumption according to the norms (SIA, 2016b, 2006). The corresponding energy rating is then assigned according to the difference (in percentage terms) between the analysed building and the corresponding standard building, as reported in Table 3.

Table 3: Building energy rating (SIA, 2016a).

Label	R minimum [%]	R maximum [%]	Comments
+	< 0	0	Positive energy buildings
A	> 0	50	Buildings with very good performance
B	> 50	100	Buildings better than the reference
C	> 100	150	Buildings consuming more than the reference. Analysis recommended
D	> 150	200	
E	> 200	250	Buildings clearly out of the norms. Analysis for retrofit requested
F	> 250	300	
G	> 300		

The normalised index R can be calculated using both the factors presented in Table 1. When the national factors (g) are used this index is called *normalised national energy consumption index* and therefore the rating is performed based on the weighted final energy. As in the case of the limits given by MoPEC, the use of national factors plays a very important role also in defining the performance of the building within the CECB label e.g. the use of renewable energy and/or a heat pump contributes to a better classification while the use of fossil fuel to a worst one.

Alongside the national CECB, a private voluntary Swiss label “Minergie” was created in the 1998 for new and renovated buildings, supported by the business community, the cantons, and the Confederation (Beyeler et al., 2009). This instrument is at the same time a guideline for energy efficient design and a quality label certifying high-energy performance. Three different labels are offered: Minergie, Minergie-P and Minergie-A, all of which are also available in “-ECO” versions defining additional requirements with regard to health and the use of environmentally friendly materials. The relevance of this voluntary label in Switzerland is reflected by the large number of certified building, with over 40 000 in 2018, more than the total number of buildings with CECB certificates in the same year (Minergie, 2018a; Rütter et al., 2008).

Minergie buildings are characterised by above-average quality, particularly in the following areas: comfort, thermal comfort in both winter and summer, low energy consumption, use of renewable energy, and own electricity production. Moreover, for new Minergie buildings (all standards), thermal energy for heating and hot water cannot be produced using fossil fuels.

The Minergie regulations of the construction standards has evolved significantly since its creation. In its current version, valid from the first of January 2018 (Minergie, 2018b), it is based heavily on the *basic module* of the MoPEC 2014. This is because the cantonal law in force cannot be infringed and is binding regardless of the regulations actually applied in the respective canton. Therefore, Minergie energy requirements for heating, hot water, ventilation and air conditioning for new buildings of all standards (Minergie, Minergie-P and Minergie-A), are the same as the ones prescribed in the MoPEC 2014 (Table 2).

To obtain a Minergie label it is necessary to calculate a Minergie index. The Minergie index represents the total weighted final energy requirement for the overall operation of the building, based on the energy reference area and weighted by the national factors (g). The total energy requirement for the operation of the building consists of several elements, that are:

- Heating, ventilation, air conditioning.
- Hot water.
- Lighting.
- Appliances.
- Technical systems.

The buildings’ own electricity production (mostly from PV) is deducted from the demand, taking into account the shares for self-consumption and feed-in to the grid.

Absolute limit values for the Minergie Index are defined depending on the construction standard, the building category and whether a new building or retrofitted is involved (Table 4).

Table 4: Limit values of the Minergie index on the total weighted final energy consumption.

	Minergie		Minergie-P		Minergie-A	
Building Type	**New construction [kWh/m²y]**	**Retrofit [kWh/m²y]**	**New construction [kWh/m²y]**	**Retrofit [kWh/m²y]**	**New construction [kWh/m²y]**	**Retrofit [kWh/m²y]**
MFH	55	90	50	80	35	35
SFH	55	90	50	80	35	35
Offices	80	120	75	115	35	35
Schools	45	85	40	75	20	20

There are other requirements in addition to these limits that the building must meet in order to be certified Minergie e.g. for Minergie-P it is necessary to achieve a performance of the envelope 30% better than that required by MoPEC. For the purposes of this study we will focus only on these limit values, as these are crucial in quantifying the energy performance gap.

In summary, the MoPEC defines the minimum standards for the consumption for space heating and domestic hot water. The CECB gives an overall assessment of the building energy demand, taking into account all its aspects regardless of the quality of the building itself. Finally, Minergie, like the CECB, assesses the overall performance of the building but applies only to exceptional buildings that should represent the most energy efficient today.

It is also important to highlight that all the limits and ratings are calculated with the use of the weighted final energy. This increases the impact of the type of energy used on the reported consumption value, to the extent that it may obscure the effect of other important factors such as the quality building envelope. Therefore, the GAPxPLORE project focused on the final energy consumption to quantify building performance. This better describes the thermal performance of the envelope and the efficiency of the heating system, which is otherwise heavily distorted by the national factors when the weighted final energy is used.

2 Literature Review

2.1 Introduction

The information on the energy performance gap in Swiss buildings is still sparse and contrasting and it is primarily based on specific case studies while there is still insufficient understanding about the broader situation. The body of research within Switzerland and internationally is continuously growing, calling for an updated overview. The objective of this literature review is therefore to obtain an overview on the energy performance gap in Switzerland, and to compare these findings with the ones obtained for other European countries in similar climatic and environmental conditions. Furthermore, we aim to answer the question posed in a report recently published by the Swiss Federal Office of Energy, namely "*whether an EPG exists in the Swiss building park as a whole*" (Frei et al., 2018). According to this report the main challenges "*are the small database and an imprecise handling of definitions and key assumptions*".

The definition of energy performance gap given in the Introduction (Equation 1) is globally accepted, but the way it is interpreted and applied varies substantially from author to author. For example, the "theoretical" energy performance can be calculated using energy performance certificate or Building Performance Simulation (BPS) software. Equally, the "actual performance" can be measured through sensors or deducted from energy bills. Further approaches exist and as a consequence, there are numerous possible comparisons which lead to different values of the EPG, both from the numerical point of view (as percentage of the actual over/under-consumption) and from the point of view of the practical meaning and implications of the observed gap. The need for this literature review originates from the great difference in approaches, methods, and definitions used until now by authors in this field. This knowledge gap was partly filled by Van Dronkelaar et al. (2016b) in a comprehensive review, however that work focused only on non-domestic buildings, and therefore not covering the residential sector.

The aim of this review is to analyse the different types of EPG found so far, to understand which are expectable due to the difference between the building performance predicted under standardized conditions and the performance under real conditions, and which are caused by malfunctioning of the technical systems and habits of the building users.

As basis for this document, an extensive international and national literature review was conducted covering peer-reviewed journal papers, academic reports, dissertations, conferences proceedings, project reports of organisations and authorities, as well as relevant international and national guidelines and standards. Section 2.2 gives an overview of the types of gaps considered. Section 2.3 presents the several assessment methods and the magnitude of the EPG. The causes and the recommendations for closing the gap are presented in sections 2.5 and 2.6. Finally, the conclusions of this literature review are drawn in section 2.7.

2.2 EPG Calculation approaches

It is a common feature of all the publications on the EPG that the calculated energy consumption and some form of measurement of energy consumption are compared. There are several ways in which the calculated consumption is modelled, leading to three main definitions of the energy performance gap, acknowledged by several authors (de Wilde, 2014; Frei et al., 2018; Rafols, 2015; Van Dronkelaar et al., 2016; Zou et al., 2018):

I. The **Regulatory EPG** compares the performance of a building established by compliance modelling based on national calculation methodologies to measured energy use. All the normative procedures, by definition, apply standardization in order to evaluate and compare different buildings observed in varying real situations (Hughes et al., 2015). The Regulatory EPG is most common approach found in international literature (Cayre et al., 2011; Delghust et al., 2015; Galvin, 2014; Herrando et al., 2016; Majcen et al., 2013; Marchio and Rabl, 1991) and Swiss literature (Bauer and Kuenlin, 2013; Frei et al., 2004; Hoffmann and Geissler, 2017a; Struck et al., 2014; Thaler and Kellenberger, 2017; Wyss and Hässig, 2016). These studies aim to investigate the difference of using default building model values (as defined in the norms) to describe the thermal behaviour of a building compared to its empirical ones. Many aspects of the current national assessment procedure might influence the performance gap.

II. The **Static EPG** compares predictions from simple performance modelling to measured energy use. The static performance gap builds on this definition to try to overcome the limitations of the norms. The models used are more complex and should be closer to reality than those applied for establishing the Regulatory EPG (I) as they do not assume compliance with standard operating conditions. The theoretical consumption is determined using a Building Performance Simulation model describing the building in its actual operating condition, rather than the consumption expected on the basis of the norms. The real number of inhabitants, an accurate indoor temperature, and the specific building properties (e.g. by considering real deterioration condition of the envelope or the outdoor environmental condition) are used to estimate the theoretical energy use, which is thereafter compared with the measured one. This approach has been widely applied in Europe (De Lieto Vollaro et al., 2015; Grossmann et al., 2016; Hughes et al., 2015; Loucari et al., 2016; Raynaud, 2014) and in Switzerland (Fux et al., 2012; Gyalistras et al., 2013; Khoury et al., 2017; Reimann et al., 2016).

III. The **Dynamic EPG** compares predictions from an advanced, calibrated, dynamic (i.e. taking into account time-dynamic properties of the building) building model to measured energy use. The dynamic building model is calibrated over several years using in-situ measurement to refine the model with its actual operating conditions. This approach needs measurements over a long time period, and therefore has been used in fewer cases in Europe (Calì et al., 2016; Jradi et al., 2018; Marshall et al., 2017) and Switzerland (Branco et al., 2004; Lehmann et al., 2017; Zgraggen, 2010).

From I to III, the methods applied for calculating the energy use become increasingly complex and factor in more and more parameters which are specific to the building, its environment and its use.

Figure 1 shows a schematic representation of different types of gaps in relation to the different stages of design, allowing to better understand when they originate and what exactly is included in the theoretical calculations.

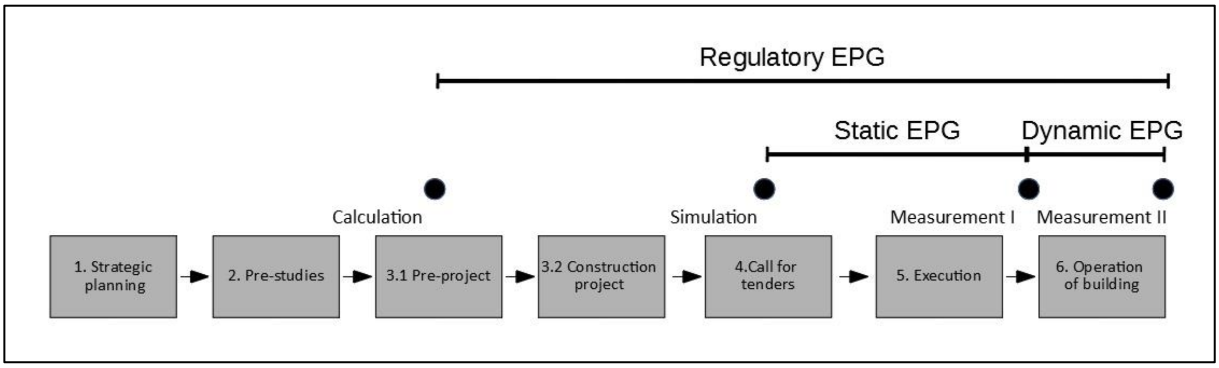

Figure 1: Energy Performance Gap in the different phases of the construction process, according to the SIA 108 (reproduced from Struck et al., 2014).

2.3 Understanding the performance gap

The EPG can be studied at various levels of detail. The predominant approach used in most studies is to consider only the annual energy consumption of the entire building for heat purposes, i.e. for Space Heating (SH) and for Domestic Hot Water (DHW). However, some analyses also include additional energy consumption for household appliances, lighting, and others. Moreover, the performance gap can also be studied at different temporal resolution using yearly, monthly, weekly, daily or even hourly data.

This section reviews the existing literature categorised by types of EPG (I, II, III, see above), together with the main findings of these studies.

2.3.1 Regulatory EPG

The most comprehensive studies on the regulatory EPG are all using datasets provided by national authorities, and therefore correspond to energy estimates following the different national standards. In most cases, the theoretical consumption is retrieved from the performance certificate to while actual consumption is established based on energy bills. Billing data is indeed a simple, accurate, and cost-effective way to measure actual energy use over a long time period.

The regulatory EPG was determined in a study for the Netherlands, where 340 000 energy performance certificates for residential buildings provided by the Agentschap-NL, a public sector organisation appointed by the Dutch Ministry, combined with data from the CBS Statistics Netherlands and energy companies were used for the analysis (Majcen et al., 2013). Results show that building with high energy performance consume more than expected (+20%) while less performing buildings consume less (-50%). Along similar lines, a recent report covering more than 115 000 residential buildings in Germany, Austria and Switzerland by Techem Energy Services (GmbH, 2017) showed that for buildings with a heat consumption of more than 120 kWh/m²y (quite inefficient buildings), the theoretical consumption is always overestimated compared to the actual. In Kelly (2011), the Standard Assessment Procedure (SAP) to evaluate the building efficiency in UK is used to calculate theoretical consumptions. Also in this case, it was found that buildings with better performance tend to consume more than calculated by the SAP, while worse-performing buildings tend to consume less.

Merzkirch *et al.* (2014) a total of 870 dwellings in 230 buildings in Luxemburg. The buildings originated from different construction periods and were dominated by medium to low energy performance. The theoretical values for single-family house were 74% higher than the actual data, while this difference was even 103% for multi-family house. Moreover, it was found that the older the buildings, the higher the EPG.

Cayre *et al.* (2011) arrived at similar finding for France using the performance certificate provided by the CEREN national database for 923 residential buildings, representative of space heating consumption in France. The calculations based on the standard model strongly overestimate space heating consumption in older housing as well as their energy savings potential. An earlier by Marchio and Rabl, (1991) study on 220 high performance dwellings came to the opposite conclusion: the actual consumption data (according to monthly meter readings from the French gas utility) were found to be on average 6% higher than the theoretical consumption (calculated following the French national standard).

Delghust et al. (2015) used the Belgium national energy performance certificate database as well as surveys of the households to collect additional information on occupation and user behaviour of 537 high performance buildings. Contrary to all other studies referred to so far, the theoretical consumption was found in this case to overestimate the energy use for SH and DHW by 25% on average. Likewise for Belgium but in line with the findings of other studies, Hens, Parijs and Deurinck (2010) concluded for 964 dwellings of low thermal performance that measured consumption may be only 50% of the calculated demand assuming standard conditions (standardized mean temperature, infiltration plus dedicated ventilation rate imposed and internal gains).

Sunikka-Blank and Galvin (2012) examined data of 3 400 German homes of medium to low thermal performance. The results indicate that actual consumption is on average 30% less than calculated. In another study for Germany the theoretical heating demand was calculated for thirty identical recently retrofitted dwellings using the national norms while the data read from energy meters were used for the actual consumption (Galvin, 2014). The analysis found a very wide variation for the EPG within the different apartments, with the gap varying between -40% (actual consumption lower than calculated) and 665% (over-consumption).

Finally, two studies by the Passive House Institute on two residential districts newly built in Germany seem to confirm the over-consumption observed in more efficient buildings (Feist et al., 2003; Peper and Feist, 2015). For these buildings, the gap is positive, meaning a larger consumption than expected, but with very small absolute values of energy in terms of kWh/m². In this case, an EPG of 13% leads to an actual consumption of 13.3 kWh/m²y instead of the calculated of 11.8 kWh/m²y.

2.3.1.1 Switzerland

Until recently, the restricted availability and accessibility of energy databases for researchers has limited large-scale analysis in Switzerland. Nevertheless, several studies were conducted on the regulatory EPG for single case studies or rather small samples of buildings, covering both single-family houses and dwellings in multi-family houses.

Thaler and Kellenberger (2017) calculated the theoretical consumption using standard values from the Swiss norm SIA 2040 for three new residential buildings in Zurich. The in-situ measurements revealed that the actual consumption exceeded the calculated consumption by 55%. Conversely but in line with the findings presented above for other countries, Bauer and Kuenlin (2013) concluded that the actual consumption of two old residential houses was 27% lower than the theoretical consumption obtained using the SIA norm 380/1.

Other studies addressed the regulatory EPG by monitoring a single variable and observing the difference between the values given by standard and measured values. In two studies the thermal transmittance of the elements of the walls was collected using over 100 measurements on 9 facades in uninsulated existing buildings and they were compared to the default values given for the same typology of construction in the Swiss performance certificate (Hoffmann and Geissler, 2017a; Wyss and Hässig, 2016). The calculated U-values were found to be higher than the measured ones, leading to overestimation of the calculated heating demand by 4% to 8%.

2.3.1.2 Implications

On the basis of the reviewed studies it can be concluded that the regulatory EPG was not close to zero in any of the cases. This is due to the intrinsic characteristics of the theoretical model, as it should be used exclusively to compare different buildings under standard conditions of usage. However, this energy rating, contained in the energy performance certificate, does not claim to foresee the real consumption of that building, and it is therefore misleading to use it as a predictor of actual consumption. While this understanding can be expected to be widely shared (at least among experts) it is remarkable that average values based on multiple case studies and larger samples differ substantially from the calculated values. While local specificities (e.g. shading) and user behaviour can obviously lead to clearly higher or lower values in reality than calculated one could expect these differences to largely cancel out when considering multiple case studies or analysing larger samples. This is, however, not the case.

According to the studies presented in this section buildings of lower thermal performance tend to consume less than calculated with norms (Cayre et al., 2011; Delghust et al., 2015; Hens et al., 2010; Majcen, 2016; Merzkirch et al., 2014; Sharpe and Shearer, 2013; Tigchelaar et al., 2011); and vice versa, buildings of high thermal performance tend to consume more than expected (Branco et al., 2004; Haas and Biermayr, 2000; Majcen, 2016). As a consequence, the energy saving target of energy retrofitting is likely to be missed if the calculated pre-retrofit energy demand is chosen as starting point instead of the actual energy demand. When assessing the effects of energy retrofitting the starting point from which to calculate the energy savings should be the building's actual consumption rather the values reported in the energy performance certificate.

2.3.2 Static EPG

Given the higher effort involved compared to studies on the regulatory EPG, the static EPG is generally studied for individual case studies or smaller samples, where BPS tools are used to model buildings with their specific features and the outcome is then compared with measured data (Foucquier et al., 2013; Loucari et al., 2016; Raynaud, 2014). In this case there is no correlation between the different local norms and the performance gap, but rather the differences result from the way in which the model of the building is generated. Several approaches can be used in BPS, grouped along three categories (Fumo, 2014):

- Engineering approaches: models built with detailed building information and weather data.
- Statistical approaches: purely statistical methods (e.g. simple linear and multiple linear regressions relating building features and/or weather conditions to energy use) and methods involving machine learning algorithms.
- The hybrid approach: a combination of both.

The first kind of methods are applicable when detailed design data are available (geometry, material properties, and energy systems features), and are therefore mostly applied to new buildings. In the work of De Lieto Vollaro *et al.*, (2015) the theoretical heating demand is simulated using the software TRNSYS for a single building and compared to its actual consumption. An EPG of 12% is found. Similar results were also found in (Hughes et al., 2015) where the result of the Cambridge Housing Model (a model for estimate total domestic energy consumption in the UK) is compared to the one obtained using billing data. An EPG of 7% is found in this case.

The second category is used for the inverse type of case, where real energy data are known but little detailed information about the building envelope or systems is available. In the study of Figueiredo et al. (2018) a multi stage calibration approach for BPS using an optimization procedure with an evolutionary algorithm is utilized to calculate building energy use. This methodology allowed to reduce the initial energy gap from 11% to 3.2%.

Finally, hybrid methods are used when a physical building model is available, but if it is incomplete or not sufficiently detailed, and therefore shall be completed. This is a typical situation when dealing with existing buildings. Loucari *et al.* (2016) used in their study a combination of assumptions on typical occupancy patterns in UK dwellings (as well as lights, appliances and window opening schedules) and measured information on the envelope (thermal transmittance, thermal bridges) to create the model of the building using the software EDSL-TAS. After comparing the result of the theoretical model with the actual data, the model was found to overestimate actual energy use by 16%.

2.3.2.1 Switzerland

The static EPG was applied in the most extensive study conducted for Switzerland (Reimann, Buhlmann and Lehmann, 2016), in which engineering observations and measurements in situ were used to tune building models for over 200 Minergie buildings. Several influential variables for SH and DHW consumption (e.g. occupation rate, internal gains) were adjusted for each specific case and the results of the energy simulation were compared with the average energy consumption over two years determined from energy bills. The study showed that new built Multifamily houses do not meet the theoretical requirements imposed by building standards. It was found that for Minergie-P MFH (the highest level of performance) the actual consumption exceeded the calculated by mere 7%, while in standard Minergie MFH (which does is comparable to the most recent mandatory building norms issued by EnDK (OFEN and EnFK, 2016)) the actual consumption was as high as 42% beyond the calculated value. A similar difference between Minergie-P and standard Minergie was found in Single-family houses but the actual consumption was always lower than the theoretical requirements: the actual consumption of new Minergie-P is 40% smaller than calculated, while in standard Minergie SFH the actual consumption is 11% smaller than calculated.

Thermal calculation software coupled with comprehensive high time resolution monitoring systems to collect information about heat flows, water flow, electricity consumption, and weather conditions were used in several other works (Fux et al., 2012; Gyalistras et al., 2013; Khoury et al., 2017). All these aimed to better understand the performance gap by further detailing the building model through the collection of more input variables, including all the unregulated loads (e.g. plug loads, external lighting), and differentiating the use (e.g. occupancy, operating hours).

2.3.2.2 Implications

The reviewed papers suggest that the static EPG (EPG II) is smaller than the regulatory EPG (EPG I), i.e. max EPG I = 665%; max EPG II = 40%. This is because a better understanding of the specificities of the building is required to complete the model for the energy simulation. The size of the gap is therefore a function of the quality of the model itself. With this type of analysis it is possible to understand the influence of all those factors that usually characterize the accuracy of the model, such as the actual number of inhabitants, the internal temperature and the ventilation rate.

The presence of the static EPG (type II) does not necessarily mean malfunctioning or incorrect use of the building systems, but more simply a discrepancy between the theoretical consumption, which is a static image of the performance of the building throughout the year (without considering the dynamics of heating loads) and the actual consumption that reflects the changes of use over time. Furthermore, the reduction of the size of the EPG when moving from the regulatory EPG to the static EPG suggests that at a significant part of the regulatory EPG is simply due to the standardised conditions used in the demand model (compare also section 2.4). Some of these standardised conditions do not seem to reflect the currently prevailing conditions.

2.3.3 Dynamic EPG

The dynamic EPG has received less attention from researchers, due to the difficulty of monitoring a building over a long period of time, generally years. In all the studies reviewed, a large number of sensors were used to monitor the operating conditions of the building (thermocouples, flowmeters, anemometers, hygrometers and solar meters) as well as the inhabitants presence over several years (Branco et al., 2004; Calì et al., 2016; Lehmann et al., 2017; Zgraggen, 2010). These parameters were used to calibrate the building model, leading to a more refined expected energy consumption calculation, which was afterwards compared with the actual data from local utilities.

This approach is more common in the world of industry and energy consulting, which typically addresses the problem of the EPG in this way. In these cases most attention is paid to reducing the gap relative to a detailed building model by changing the operations of the building or its components in order to reduce the actual energy consumption (Colombini and Energo, 2017; Minergie, 2018a; Ott et al., 2014). This type of analysis, however, are very specific and linked to individual case studies.

In Calì et al. (2016) three buildings with 30 apartments each are monitored after retrofitting for 5 years at high time resolution. To evaluate the real energy performances of the refurbished buildings, each room of the apartments was monitored in terms of temperature, relative humidity, CO_2, volatile organic compounds (VOC), light on the ceiling (Lux), infrared/visible light, and window opening sensors (open/closed). This information was then used to steadily update the theoretical model of the building. A significant reduction of the EPG was found over the years, from 117% the first year, to 107% in the second, to 41% in the third, and to 60% in the fourth (the value for the third year is lower because of a particularly warm winter).

In the study by Marshall et al. (2017) the calculated consumption for a typical pre-1920s UK house is obtained using the SAP specifications in the model of DesignBuilder. When compared with the measured consumption, an EPG of 18.5% was found. Afterwards, accurate measurements of air permeability and U-values were made in-situ and they were used in the simulation instead of the standard values in order to obtain a refined theoretical consumption. Thanks to this better alignment, the EPG was reduced to 2.4%.

In Jradi et al. (2018), a new energy performance monitoring and evaluation tool (ObepME) is used. The results of a calibrated dynamic building energy model are compared to the actual collected data to evaluate the dynamic energy performance gap. The results revealed an EPG for heating consumption of −2.85%.

2.3.3.1 Switzerland

In Switzerland dynamic models have so far been applied only for single building case studies (Branco et al., 2004; Lehmann et al., 2017; Zgraggen, 2010). Branco et al. (2004) monitored the most important energy flows of an MFH with 82 apartments for three years. A data logger was used to gather instantaneous sensor signals every 15 seconds and to simultaneously calculate the energy flows. The initial EPG was estimated at 54%, with the measured consumption equal to 246 MJ/m^2y and a theoretical value of 160 MJ/m^2y. However, when the metred values (e.g. internal temperature, water consumption) were used in the simulation model, a new theoretical value of 251 MJ/m^2y was obtained, which is very close to the measured consumption (EPG -2%). This means that the envelope was well executed and that the thermal performance of the building was well understood.

Another long-term study on a student residence in Geneva showed that a carefully calibrated model is essential not only in order to properly model the technical systems, but also the inhabitants' behaviour (Lehmann et al., 2017). The analysis revealed that closed window shades and open windows occurred much more frequently (on average 40% of the windows were steadily obscured by closed shades) than originally accounted for in the building model. After these and other corrections, the EPG was considerably reduced from 81% to 13%.

2.3.3.2 Implications

The cases presented show that the dynamic EPG can be very narrow, and in any case smaller than the static EPG. This is because a continuous monitoring of the building is essential to understand its operation and then allows to properly model it. Moreover, it is easier to find a real malfunctioning of the building systems when the building is accurately modelled (Colombini, 2017). It may therefore be concluded that - regardless of the size of the regulatory and static EPG - the dynamic EPG should always be as close as possible to zero, as it is indicative of an actual operation outside of its expected range.

2.4 Magnitude of the energy performance gap

To summarize the results discussed above, Table 5 displays an overview of the results found in the reviewed papers, with their respective findings in terms of the magnitude of the EPG using the Eq.1.

Table 5: Overview of the performance gap in Europe according to the reviewed papers; EPG class I = regulatory, II = static, III = dynamic.

Reference	EPG class	EPG	Country	Number of case studies	Thermal performance
(Majcen et al., 2013)	I	- 50% +20%	Netherlands	193 856	Low High
(Sunikka-Blank and Galvin, 2012)	I	-30%	Germany	3 400	Diverse
(Merzkirch et al., 2014)	I	SFH -74% MFH -103%	Luxemburg	230	Diverse
(Galvin, 2014)	I	-40% to 665%	Germany	30	Diverse
(Bauer and Kuenlin, 2013)	I	-27%	Switzerland	2	Low
(Marchio and Rabl, 1991)	I	6%	France	82	High
(Feist et al., 2003)	I	13%	Germany	1 260	High
(Delghust et al., 2015)	I	25%	Belgium	537	High
(Thaler and Kellenberger, 2017)	I	55%	Switzerland	3	High
(Reimann et al., 2016)	II	SFH -11 -40% MFH 7-42%	Switzerland	214	High
(Loucari et al., 2016)	II	16%	UK	1	High
(De Lieto Vollaro et al., 2015)	II	12%	Italy	1	High
(Hughes et al., 2015)	II	7%	UK	2 000	Diverse
(Branco et al., 2004)	III	From 54% to -2%	Switzerland	3	High
(Calì et al., 2016)	III	From 117% to 60%	Germany	3	High
(Marshall et al., 2017)	III	From 18.5% to 2.4%	UK	1	High
(Jradi et al., 2018)	III	-2.85	Denmark	1	High

According to Table 5 the magnitude of the EPG tends to narrow from one EPG type class to another (I to III). For the regulatory EPG, it can be concluded that it is negative for low performing building and positive for high performing ones. This it means that using the national norms to evaluate the energy consumption of a residential building typically leads to over-estimation when dealing with old/low performing buildings, and to under-estimation when dealing with new/high performing ones.

As summarized in Table 5, the static EPG (II) found in the reviewed papers is always positive. The reason is to be found in the type of buildings examined, as they were mostly new and high performing buildings. As already mentioned above, the reduced size of the gap compared to the regulatory EPG can be explained by the more accurate building model.

When analysing the national building stock, a negative average regulatory EPG is found, implying a lower actual energy consumption than expected according to the national standards (Majcen et al., 2013; Merzkirch et al., 2014; Sunikka-Blank and Galvin, 2012). This phenomenon it is due to the high share of old buildings in the stock. In most EU countries, half of the residential stock was built before

1970, i.e. before the first thermal regulations (European Commission, 2018). Modern and more performing buildings are in fact designed and built according to the same standards that are then applied to evaluate them and predict their consumption. This could explain the relatively smaller magnitude of the EPG in newer buildings. Instead old buildings, built according to other (or no) criteria, respond differently when evaluated with the current standards (e.g. homogenous internal temperatures, homogenous thermal properties of the envelope), resulting in a larger EPG.

While, compared to old buildings, the EPG is relatively small for buildings with high thermal performance, the EPG range is still wide, spanning from less than 10% to 50% and more. No direct relationship between the size of the EPG and the type (I, II, III) can be identified based on the reviewed case studies. Apart from user behaviour one further important explanatory factor may be the substantial difference in energy performance within the high-performance category. Very few studies are available on buildings with very high thermal performance (Minergie-P according to Reimann, Buhlmann and Lehmann, 2016 and Passive House according to (Feist et al., 2003; Peper and Feist, 2015) .These studies seem to indicate a smaller EPG for buildings with very high thermal performance or even outperformance compared to the standards (negative EPG). Given the anyway lower absolute values (in kWh/m^2y) of buildings with very high thermal performance this seems to indicate a substantially lower risk of overconsumption. Further case studies would be required to confirm or to falsify this finding.

Finally, as shown in Table 5, the static EPG of the reviewed paper is always positive. The reason is to be found in the type of buildings examined, as they were mostly new and high performing buildings. As already mentioned above, the reduced size of the gap compared to the regulatory EPG can be explained by the more accurate building model.

2.4.1.1 Switzerland

Table 6 displays an overview of the most relevant research in Switzerland, with their respective findings in terms of the magnitude of the EPG.

Table 6: Overview of the performance gap in Switzerland according to the reviewed papers; EPG class I = regulatory, II = static, III = dynamic.

Reference	EPG class	EPG	Number of case studies	Buildings type	Thermal performance
(Thaler and Kellenberger, 2017)	I	55%	3	MFH and mixed use buildings	High
(Frei et al., 2004)	I	25% +152%	6	MFH	High
(Zgraggen, 2010)	I	70%	10	MFH	High
(Bauer and Kuenlin, 2013)	I	-27%	2	SFH and MFH	Low
(Hoffmann and Geissler, 2017b)	I	-38%	8	MFH	Low
(Reimann et al., 2016)	II	SFH -11% -40% MFH 7% to 42% Office 5% to 18%	214	SFH, MFH and offices	High
(Khoury et al., 2016)	II	45% +173%	10	MFH	High
(Zgraggen, 2010)	III	257%	1	MFH	High
(Lehmann et al., 2017)	III	81%	1	MFH (student house)	High
(Branco et al., 2004)	III	54%	3	MFH with commercial	High

Table 6 shows that in most case studies the actual energy consumption is higher than the calculated one (EPG > 0). On the other hand, the few cases dealing with low performance buildings feature a negative EPG. In conclusion, these findings for Switzerland are consistent with the ones from the international literature.

2.5 Causes of the performance Gap

The performance gap is a complex phenomenon which is influenced by numerous factors. It is hence challenging to identify which ones are contributing to the performance gap and to which extent. Multiple causes were found in the literature review, all related and hardly distinguishable in defined categories, as the inaccuracy of the building model, the occupant behaviour, the complexity of the design or the on-site workmanship (Van den Brom et al., 2017; Van Dronkelaar et al., 2016).

Many of the causes highlighted at European level have also been found in Switzerland, and among these the most frequent are:

1. Uncertainty in Building Energy Modelling
2. Malfunctioning Equipment
3. Measurement and Control Systems
4. Occupant Behaviour
5. Changes after Design

All of them will be briefly presented and discussed in this section.

2.5.1 Uncertainty in Building Energy Modelling

This section includes all the identified reasons why a parametric model may not properly describe a real building. These limitations are common to any BPS process.

Two principal inaccuracies related to the parametric settings have been identified in the literature: the expected indoor temperature (Bauer, 2013; Branco et al., 2004; Frei et al., 2004; Hughes et al., 2015; Schröder et al., 2014) and the U-values assumed for building elements (Hughes et al., 2015; Loucari et al., 2016; Merzkirch et al., 2014). These two parameters are indicated as the most sensitive on the result of the energy simulation (Marshall et al., 2017; Merzkirch et al., 2014).

Hoffmann and Geissler (2017b) found that the too high U-values used for calculations and too low indoor air temperatures given by national norms were the main factors for the regulatory EPG observed in their case studies. These two deviations compensate each other to some extent. These conclusions were confirmed by Wyss and Hässig, (2016), who performed over 100 measurements on different kinds of walls types built before 1985 and found that the U-values used for calculations exceeded the measured ones by 10% to 200%. Instead Lehmann, Khoury and Patel (2017), in a work based on a single newly built case study, arrived at the opposite conclusion for the U-values, with the measured data exceeding the planned (0.12 W/m^2/K vs. 0.09 W/m^2/K) during the field inspection. The same paper showed that the average temperature across several rooms was 21°C, which is 1°C higher than assumed in the norms (SIA standard). The consequence on the EPG of a variation of 1-2 °C in the room temperature is stated in several studies (Schröder et al., 2014; Struck et al., 2014). Also (Hughes et al., 2015) indicated the internal temperature as the most significant parameter in the modelling process, and showed its influence on the EPG.

While it can be argued in the case of indoor temperatures (as well as for several other indicators) whether the values according to the norms are too low or whether user behaviour is at fault, there is strong indication that an indoor temperature of 20°C (as assumed by standards) nowadays does not represent a widely accepted set-point temperature (Frank, 2005).

Another major source of uncertainty in BPS, on which there is consensus in the literature, are the weather conditions used in the simulations. The work of Thaler and Kellenberger (2017) showed that the weather data used in the study was not climate adjusted, becoming the main cause for the energy performance gap. The same finding was confirmed by Branco *et al.* (2004), who highlight the importance of choosing the proper weather station when simulating the performance of a specific building. Evidence of the central role of the selection of the appropriate weather file and its consequences on the EPG is also reported in other studies (Bauer and Kuenlin, 2013; Struck et al., 2014).

Several studies concord that another important difficulty detected in the BPS process is the geometry definition of the building (Gyalistras et al., 2013; Hughes et al., 2015). Herrando et al. (2016) found that the discrepancy between the real and the simulated buildings' surface area is on average 8%, leading to a substantial difference in the energy consumption.

The actual ventilation air change rate is another parameter that may vary significantly in practice, as it is both difficult to regulate and make regular checks of the performance (Kragh et al., 2017). An incorrect air flow rates, which play a major role in the space heating demand calculation, was indeed found as cause of the EPG in several studies (Bauer, 2013; Branco et al., 2004; La Fleur et al., 2017). Khoury et al., (2017) demonstrated that an elevation of the air flow rate of 0.2 m^3/h.m^2 led to an increase of about 5 kWh/m^2 in the heating demand. In the same study, measurements on 20 retrofit buildings showed that the direct air flow rates were 1 m^3/m^{2}h on average, and 1.5 m^3/m^{2}h when considering the indirect air flow resulting from window openings, instead of the standard value of 0.7 m^3/m^2h.

Other factors that can influence the building's performance calculation procedure are the default value for the air tightness of the building envelope, the default reported characteristics of the space heating system (e.g. too high efficiency), and the formula for calculating the domestic hot water consumption (Delghust et al., 2015); additional factors are the difficulty of modelling the solar gains and the thermal inertia of massive walls (De Lieto Vollaro et al., 2015), the incorrect calculation of the shading factor (Bauer and Kuenlin, 2013), and the difficulty in reproducing the moisture storage properties of the building (Struck et al., 2014).

2.5.2 Malfunctioning Equipment

Malfunctioning equipment or faulty settings in the building systems fall into this second category. Several studies underlined that detailed monitoring of the building heating, ventilation and air-conditioning (HVAC) system is crucial to unveil discrepancies between theoretical and real heat consumption, especially for innovative systems that often do not work as expected (Branco et al., 2004; Calì et al., 2016; Herrando et al., 2016; Struck et al., 2014). Malfunctioning of the heating system, is often a cause of the difference between actual and expected consumption (Galvin, 2014; Hughes et al., 2015).

An example of how a malfunctioning of the heating system, in this case heat pumps, can affect the EPG is reported in the work of Calì et al. (2016a). The same types of heat pump in different buildings were monitored for two years, showing a large variation in their performance factor due to a malfunctioning of some of the pumps.

With regard to technical problems, the examples in literature are numerous and diverse. Often the ventilation system is not working at the design specification, as was found by Aiulfi et al. (2010) for the majority of cases in Swiss buildings. A further reason is rapid calcification (chalk build-up obstructing the pipes) of the DHW system, resulting in lower system efficiency (Calì et al., 2016). In another study, the EPG was reduced by 15% after having resolved malfunctioning of the solar thermal system and having optimized the hydraulic balancing of the heating system (Khoury et al., 2017). Reimann, Buhlmann and Lehmann (2016) confirmed these results by demonstrating that proper set-point adjustments (temperature set point, air changes per hour, etc...) of HVAC systems can have a much larger influence on the level of energy consumption than user behaviour.

2.5.3 Measurement & control systems

Multiple studies found that the faulty installation of measurement and control systems and measurement inaccuracies can lead to incorrect interpretations of the energy behaviour of the building and subsequently to an EPG (Sagerschnig, 2015; Struck et al., 2014). Fux *et al.* (2012) found evidence of a widespread malfunctioning of all the measurement equipment in the analysed case study, resulting in an incorrect definition of the actual consumption. A study by Wyss and Hässig (2016) illustrated the need for a qualified expert to perform the measurements of the actual values. For specifying U-values, some clear limits of the measurement devices' capabilities were found, making it crucial to have an experienced user in order to prevent errors.

2.5.4 Occupant Behaviour

Characterisation of occupant behaviour is a major challenge in BPS. The way the inhabitants actually use the buildings is often very far from their expected use, potentially resulting in a variable energy consumption over time and accordingly a variable performance gap (Galvin, 2014; Khoury, 2014; Raynaud, 2014; Reimann et al., 2016; Schröder et al., 2014).

The occupants' behaviour has been identified as one of the causes for the EPG, by either increasing or decreasing it (Calì et al., 2016). As already mentioned above, one of the decisive factors is the choice of the indoor temperature (Herrando et al., 2016; Khoury, 2017). Schröder et al. (2014b) explained the higher average room temperatures in new as compared to old buildings as a physiological reaction of the inhabitants. The study shows that some physical perceptions, such as feeling cold in unheated rooms, or in the vicinity of cold walls or window surfaces, occur less frequently in highly insulated buildings and cause less direct intervention of the inhabitants in the operation of the heating system.

In a study over six identical houses, it was found that the actual consumption varied by almost a factor of two just due to differences in user behaviour (Marchio and Rabl, 1991). For a Swiss student residence, Lehmann, Khoury and Patel (2017) found that 20% of the windows of kitchens and living rooms were permanently open and 40% of the windows of bedrooms were obscured by closed shades. These habits of the inhabitants led to lower heat gains by sunlight, resulting in higher heating demand and energy consumption than expected. It is interesting to note that in a different case study, the manual blind repositioning by the occupants was resulting in higher solar heat gains and a lower heating consumption (Gyalistras et al., 2013).

2.5.5 Changes after Design

During the design of a building, but even after its construction, it is not uncommon for the planned use to be subject to modifications. These changes can occur due to external constraints, building owner decisions or policy issues. Deviations from the initially planned use can have consequences on the EPG. The most common case found in Switzerland is the difference in the number of users between design and operative phase (Gwerder et al., 2013; Khoury, 2017). Struck *et al.* (2014) found that the EPG of five of the seven analysed buildings could be explained with a different use of the building itself, as an there was an additional use of the buildings than was determined during the design (e.g. cafeteria with professional equipment instead of a normal household equipment and a second coffee machine).

2.6 Reducing the energy performance gap

Reducing the energy performance gap does not only mean getting the building to consume as calculated, because as already seen in many cases the actual consumption can be lower than expected, but it also implies more accurate calculation of the theoretical consumptions, to bring them closer to reality.

Most of the solutions found in the literature to reduce the gap have gone in one of two directions. The first focusses on correcting and improving the parameters that are used in the theoretical calculations and do not conform to reality (e.g. internal temperature, ventilation rate, thermal transmittance of the envelope), sometimes even successfully changing national standards. The second deals with monitoring and controlling the building's energy systems to solve the technical problems that cause actual consumption to be larger than expected. Some works combine the two, promoting more legislative or policy-oriented approaches to improve the phases of design, construction, and use of the building.

2.6.1 Accuracy of calculated values

Most of the remedies to reduce the EPG presented in the reviewed papers have addressed technical measures and related calculation problems encountered in specific case studies. Consequently, the information is sparse and not yet integrated in the building design process. Generally it can be stated that the norms for calculating the building's thermal performance should be improved in terms of data quality and disaggregation (energy consumption of specific equipment and surface area), in order to better describe local characteristics (Herrando et al., 2016; Loucari et al., 2016). Delghust et al., (2015) suggested that, beside an accurate evaluation of the air tightness of the envelope, the realistic estimation of user behaviour is a fundamental challenge for bridging the gap. The problem is indeed to define which user profile to consider as the standard one. Many authors suggest to modify the internal temperature for the different areas of the building, as the average room temperature in the regulations is assumed to be 20 °C, but measurements in old buildings show a mean room temperatures of 17 °C for certain areas and temperatures clearly above 20 °C for living areas (Branco et al., 2004; Frei et al., 2017; Merzkirch et al., 2014).

There have been a range of suggestions on how to improve the Swiss calculation methods, such as reducing the wind velocity for the calculation of the external heat transfer coefficient and consequently U-value of the wall (given the lower wind speed in cities), or using a b-factor (adjustment factor for thermal transmittance) of 0.5 instead 0.7 in order to better describe the indoor air temperatures of unheated building zones (Hoffmann and Geissler, 2017b). Furthermore, as suggested by Lehmann, Khoury and Patel (2017), when using a ventilation rate of 1 $m^3/(m^2h)$ instead of the standard value of 0.3 $m^3/(m^2h)$ when describing forced ventilation with heat recovery, the calculated demand corresponds to the actual one. This is a first indication that the default calculations on ventilation may be too low, without however providing stringent proof. Another possibility to tackle calculation problems is suggested by Thaler and Kellenberger (2017), who propose to compare energy performance on a per capita basis as well as per heated floor area. This would account for the considerable variance in living area per capita, where there is still an un-used potential for implementing improvement measures.

2.6.2 System adjustment, monitoring and control

It is difficult to have a complete overview of all the technical problems encountered in the reviewed works, as technical problems are not the main issue and should be considered case by case (Calì et al., 2016). Several authors found that the occupants' acceptance of a system is a key factor for reaching the expected consumption, as inappropriate use always leads to overconsumption (Galvin, 2014; Merzkirch et al., 2014; Schröder et al., 2014). Calì et al. (2016a) found that the higher energy consumption was due to a lower performance of the heat pump than expected, caused by an unplanned increase of the hot water temperature. Reducing the hot water temperature to the design temperature (from 60°C to 42°C) reduced the EPG. Several authors agree that ventilation is one of the parameters calling for more attention in the realization and monitoring phase, as it can be easily modified by users (Grossmann et al., 2016; Struck et al., 2014).

Cayre *et al.* (2011) discusses which technologies are most likely to be negatively impacted by occupants' behaviour, and which are most robust. Moreover, Schröder et al. (2014) clearly stated that "the influence of individual user behaviour on the integral energy consumption will further rise, because the energy release into the living environment gets more and more disconnected from the human perception (bio-feedback)". This means that it will be gradually more difficult for the user to understand and quantify the impact of his actions on the energy consumption (e.g. raise the thermostat by one degree or leave a window open). To tackle the problem of the relevance of the user, some Behaviour Change Programs (BCPs) have been already tested to achieve a reduction of the overall energy consumption (Anda and Temmen, 2014). This study shows that significant results can be achieved, provided that certain key aspects (e.g. community engagement through workshops and focus group, coaching and feedback programs, and satisfaction survey) are integrated in the programs.

In Switzerland, Khoury, Alameddine and Hollmuller (2017) modelled several technical measures, including elimination of malfunctioning of the solar thermal system, gradual reduction of the indoor temperature, hydraulic balancing of the heating system and adjustment of the heating curve and the settings of the heat recovery ventilation system. Through these corrections, the EPG was drastically reduced. Continuous performance monitoring of the building has been identified as an important solution by several authors (Branco et al., 2004; Reimann et al., 2016; Sagerschnig, 2015). An effective usage of BPS can contribute to this objective (Struck et al., 2014). The work of Colombini and Energo (2017) in this direction is notable, in which energy modelling (making use of artificial intelligence) and energy monitoring are coupled to identify EPG in buildings.

2.6.3 Building energy labelling and monitoring policies

Engineers and architects have the knowledge to construct buildings that can perform well but the legislative framework plays an essential role to encourage good practice both in construction and operation. The EPBD has supported the quest for energy efficient buildings in the EU (The European Parliament and the Council of the EU, 2003). However, the EPBD does not require any mandatory control to verify the actual consumption of the building once in use. Integrating an appropriate measurement and verification system into the EPBD may contribute to close the gap, or at the very least to better identify its causes. In 2010 the recast of the EPBD added the possibility of regular inspections of the HVACs in buildings, to monitor their performance (The European Parliament and the Council of the EU, 2010). However, their full scale implementation has not yet been initiated (Droutsa et al., 2016). Again in 2018, the new EPBD (The European Parliament and the Council of the EU, 2018) required all the Member States to ensure that residential buildings are equipped with the functionality of continuous electronic monitoring that measures systems' efficiency and informs building owners or managers when it has fallen significantly and when system servicing is necessary.

In this direction, the UK department of Energy and Climate Change introduced the energy-saving opportunity scheme (ESOS) in order to promote operational management in buildings (Van Dronkelaar et al., 2016). In substance, this is a compulsory energy assessment to identify energy savings in companies with more than 250 employees or with an annual turnover of more than 50 million Euro. The same approach may be used for large MFH buildings.

Burman et al. (2014) suggest that building designers or construction contractors should have the responsibility of verifying energy performance of their buildings after completion. Findings of the study shows that comparing actual energy performance with theoretical one under same operating conditions could help to identify the over-consumption due to poor construction practices, allowing to make the constructor responsible for resolving the issues.

It is also well known that analysing specific household types and building characteristics contributes to a better understanding of the influence of the occupant on the EPG. The results of the work of Van den Brom et al. (2017a) show that the building characteristics have a higher impact on the elderly than on younger people (e.g. given the longer time spent at home and the greater demand for thermal comfort), and that low-income households consume more gas per m^2 than households with a high income for all types of housing, and not just for the less insulated dwellings as could be expected. This could be an incentive for policy-makers to prioritize building renovations for the elderly and low-income inhabitants.

In Switzerland, a study on the cantonal energy policy showed considerable diversity in policies: commitment on the energy reduction and priorities in environmental objectives varied greatly between the cantons (Müller et al., 2014). Moreover, none of them achieved the maximum rating in the indicator "Energy Efficiency Requirements", which evaluates the actions taken to reduce heating consumption in existing buildings. On a scale from 1 (low) to 5 (high), the majority of cantons scored only a 2 or lower on this indicator. The CECB was mentioned as a tool for ranking the building performance, but at the same time it can be a powerful instrument to gather information on the operational data and on the status of the building stock.

Overall, progress is being made in improving energy policy, especially in some leading cantons. Nevertheless, from a national perspective, a full range of policy measures is still needed. Information, advice, incentives, and rules play an essential role and for a maximum effect, they must be harmonised. However, governments continue to deal with the delicate task of balancing the principle of not interfering in business affairs with the recognition of the serious consequences of energy waste and climate change (Jonlin, 2014).

2.7 Conclusion

The Energy Performance Gap in buildings is defined as the difference between theoretical consumption (representing a forecast of energy consumption) and the measured consumption. The literature review aimed to provide an overview of the approaches applied by researchers and practitioners to date, trying to better define and frame the problems associated to the performance gap in Europe and in Switzerland.

Three interpretations have been identified, distinguished by the way in which the calculated consumption is modelled: a regulatory, static, and dynamic performance gap. The regulatory performance gap, that compares the performance of a building under standardized national conditions to measured energy use, is the most widely used.

Numerous studies reveal that better performing/newer buildings are consuming more than predicted by the norms (positive regulatory EPG) while worse performing/older buildings are consuming much less than expected (negative regulatory EPG). A very large variation was found in the reviewed papers, with regulatory EPG values ranging between -103% and +665%. These extreme values include peculiar case studies, but they are nevertheless useful to illustrate how much actual consumption can be far from those calculated by norms or energy certificates. However, this type of EPG is most frequently comprised in the range between -40% and +55%. In Switzerland, based on 27 case study buildings (not representative of the building stock) a wide spectrum of values was found, ranging from a minimum of -40% to a maximum of +257%. This result lends support to the finding in international literature, at least in showing the existence of a significant energy performance gap also in Switzerland.

Given the limited number of studies on the other two classes of EPGs (static and dynamic) it is difficult to draw general quantitative figures as above, but from a qualitative point of view it can be concluded that both EPGs are smaller than the regulatory EPG, demonstrating that it is feasible to close these gaps to some extent by using a more accurate theoretical model and a regular monitoring of the building systems.

While, compared to old buildings, the EPG is relatively small for buildings with high thermal performance, the EPG range is still wide, spanning from less than 10% to 50% and more. No direct relationship between the size of the EPG and the type (I, II, III) can be identified based on the reviewed case studies. Very few studies are available on buildings with very high thermal performance (Minergie-P according to Reimann, Buhlmann and Lehmann, 2016 and Passive House according to (Peper and Feist, 2015) .These studies seem to indicate a smaller EPG for buildings with very high thermal performance or even outperformance compared to the standards (negative EPG). Given the anyway lower absolute values (in kWh/m^{2}y) of buildings with very high thermal performance this seems to indicate a substantially lower risk of overconsumption. Further case studies would be required to confirm or to falsify this finding.

The literature review reveals that a number of factors determine the size of the EPG, among which the limitations of the building performance simulation process (e.g. the incorrect definition of the envelope thermal transmittance or of the indoor temperature), malfunctioning equipment and the occupant behaviour are the most important. The same causes have been indicated as the most common for both Switzerland and other EU studies. To date, strategies proposed for closing the EPG have had two different objectives. The first point in the direction of correcting and improving parameters that are used in theoretical calculations and do not conform to reality, with the objective of obtaining a more reliable building model. The second deal with monitoring and controlling the building's systems to find tailored solutions for each specific cause and therefore they cannot be generalized for the entire building stock.

This review is a first step enhancing our understating of the energy performance gap in Swiss buildings and highlighting the need for this research. A deeper analysis using large-scale datasets, containing actual energy consumption data as well as buildings design demand data is indeed urgently required.

3 Datasets

3.1 Introduction

In GAPxPLORE, calculated and actual energy consumption data are based on four sources. First is the Swiss Cantonal Energy Certificate for Buildings (CECB) database, managed by the FHNW. The CECB dataset provides a relatively representative subsample of the Swiss building stock (including also existing, older buildings, many multi-family dwellings etc.). Second, we used the Swiss Solar Agency data that was collected as a part of applications for the Swiss Solar prize and consists of buildings, which can be considered as examples of best practice in terms of thermal as well as electrical performance (new and recently renovated buildings). Third is the Switzerland-wide Minergie database to which SUPSI has access. As fourth, the Energo platform (Energotools) contains historical data of heat and electricity consumption on weekly basis for several years in more than 5,000 different buildings. The dataset includes metered energy data for these buildings. The know-how of the Energo engineers working in several case studies allowed to identify the reasons for the gap of performance related with technical building system, occupant behaviour and presence patterns (Section 7). In this chapter the characteristics of all the different database used will be introduced.

3.2 CECB dataset

3.2.1 Introduction

The Cantonal Energy Certificate for Building was introduced 2009 in Switzerland in the wake of the EPBD (The European Parliament and the Council of the EU, 2003). It was designed to be used by certified CECB Experts to provide a quick and cost-effective way of estimating the energy performance of existing buildings. Thanks to a simple double energy scale, the efficiency of the building envelope as well as the efficiency of final energy use can be easily visualized. Since its introduction almost ten years ago, the CECB has been continuously improved and its functions have been enlarged, with more improvements being planned for the future. CECB has since established itself in the local laws of most cantons, as well as in the MoPEC (Conferenza Cantonale dei Direttori dell'Energia CDE, 2014). Numerous cantons fund nowadays the realization of a CECB.

CECB data sets – which include the actual "CECB document" (often referred to as "certificate") - are stored in a central database. Access to the complete CECB database is only available to the company commissioned with the coding of the software tool. Administrators of the CECB operative centres and officials of the cantonal offices of energy (Energiefachstellen) in Switzerland have access to this database on varying levels, whereas certified CECB experts have access only to the data sets they have entered themselves and published for their clients. Clients are typically given a paper and/or electronic PDF exemplary of their CECB-outputs, only. For the general public, it is only possible to cross-match a known certificate number to its latest registered version, but without access to the contents (should the version they have not be the most recent). This can be done via the public web site.

Due to a continuous development of the tool since its beginnings in 2009, there are different "types" of data sets stored in the database, today.

- From 2009 to the end of 2016: simple CECB (files type "G"[1]) for a quick appreciation of "old enough" buildings in Switzerland, with a low level of possible numerical adaptations by the Expert. Output: CECB document.
- From fall of 2012 onwards: detailed CECB "Plus" (type "GP") providing the Expert with extensive input possibilities. Output: CECB document and "CECB Plus" = an expert report comparing up to 3 different strategies of (energy focused) refurbishment.
- From 2013 onwards: CECB Plus for new buildings (type "GN"), less than 3 years old or in the planning stage. Same outputs as GP, the strategies focused on here being the comparison of variants (building envelope, technical amenities...) rather than energy retrofit.

3.2.2 The CECB Expert

Anyone having appropriate professional experience and adequate background can apply anytime for the title of "CECB Expert" by sending his or her application to the nearest operative centre ("Betriebszentrale"). After evaluation, the applicant will be invited to complete a course focused on the tool itself, take some tests and will finally be bound by contract as a certified CECB Expert.

CECB Experts can be found online by anyone wishing to have a building certified or to have the energy retrofit evaluated. The Expert of choice is then commissioned by the building owner (typically) to issue a CECB certificate. For this purpose, the Expert will need to receive the pertinent data and information from the building owner. The Expert is required to do a site visit in order to get a good impression of the building. Based on the information received and the site visit, the Expert enters all the data into the CECB Database.

3.2.3 Size of the CECB dataset

Between 2009 and late 2018, only buildings belonging to the following four categories defined in SIA 380/1 (SIA, 2016b) could be certified: simple family houses (one to two dwellings), multi-family houses (more than two dwellings in one building), "simple" schools and administrative buildings (without any cooling or air conditioning). Since the end of 2018, three more "usages" are possible (which extend the term "category", since there can be more than one usage per category); hotel, sale/retail and restaurants. Also, since the end of 2018 mixed usages are more readily possible, e.g. "sale/retail" on the ground floor, dwellings and/or office space on upper floors. There are now four non-residential and three residential uses.

At the end of 2018, the database contained over 78 000 datasets of buildings, overall. From 2010 through 2016, approximately 3 000 – 5 000 new building certificates were entered per year (see Figure 2).

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[1] Old "G" data sets can be converted to the more advanced GP-file type. However, such converted data sets require additional data input for HVAC, electrical household appliances and details in regard to costs prior to being able to run a new calculation.

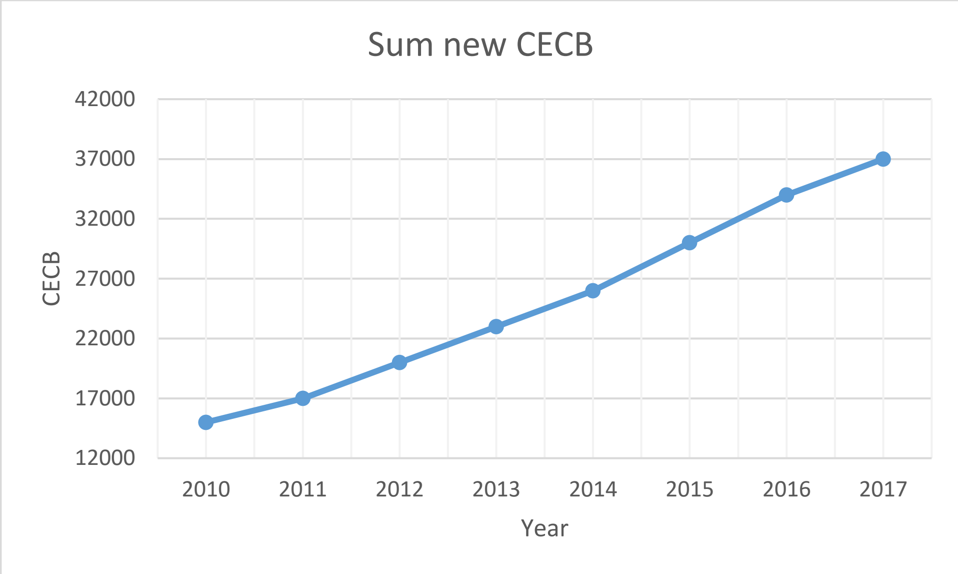


Figure 2: Development of available number of CECB data sets over time (disregarding the first approx. 15'000 which were based on the first version of the tool and have non-negligible shortcomings). The time span covered is 2010 – 2016.

Due to changes in legislature in western Switzerland, the number of new buildings entered has significantly increased since 2017. Over 13 500 new GP certificates were issued in 2018 (first versions, all categories), or a total of 33 000 new certificates in the three-year period from January 2016 until December 2018.

Certificates are eligible for an update during their 10 years-validity period. Taking such updates into account, the total number of certificates over the last 3 years rises to 38 000. The total number of certificates between August 2009 and December 2018 approximates 79 000.

The vast majority of certified CECB buildings has a residential use: simple family houses (58%), then multi-family houses (38%) and only 3% for administrative buildings and 2% for schools. Figure 3 summarizes the years 2009-2018 (as hotels, sale and restaurants are quite new these usages are not represented).

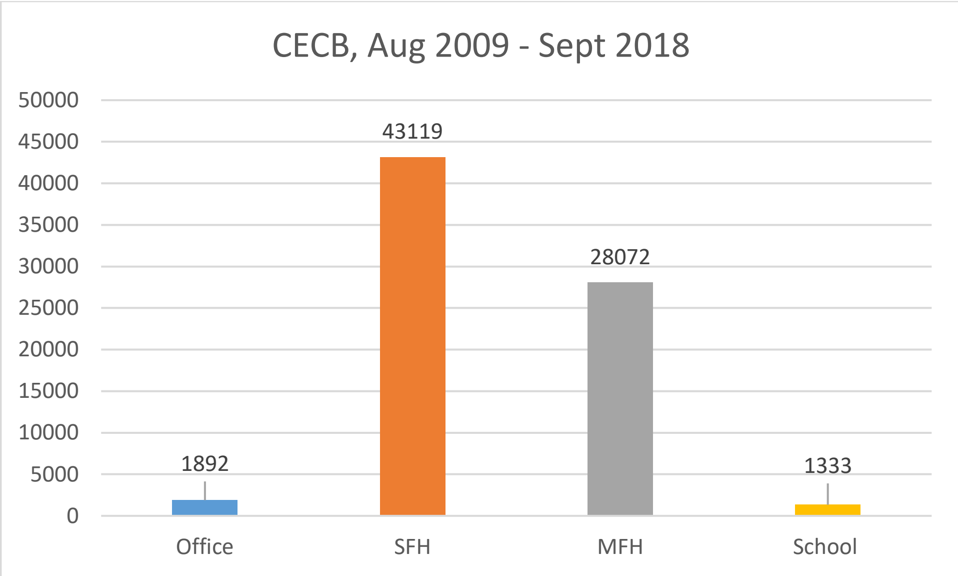


Figure 3: Distribution of Certificates across the available categories / usages.

Figure 4 shows the kind of files for a representative year 2016 (the old file type G was discontinued at the beginning of November). New buildings are far less represented than existing buildings.

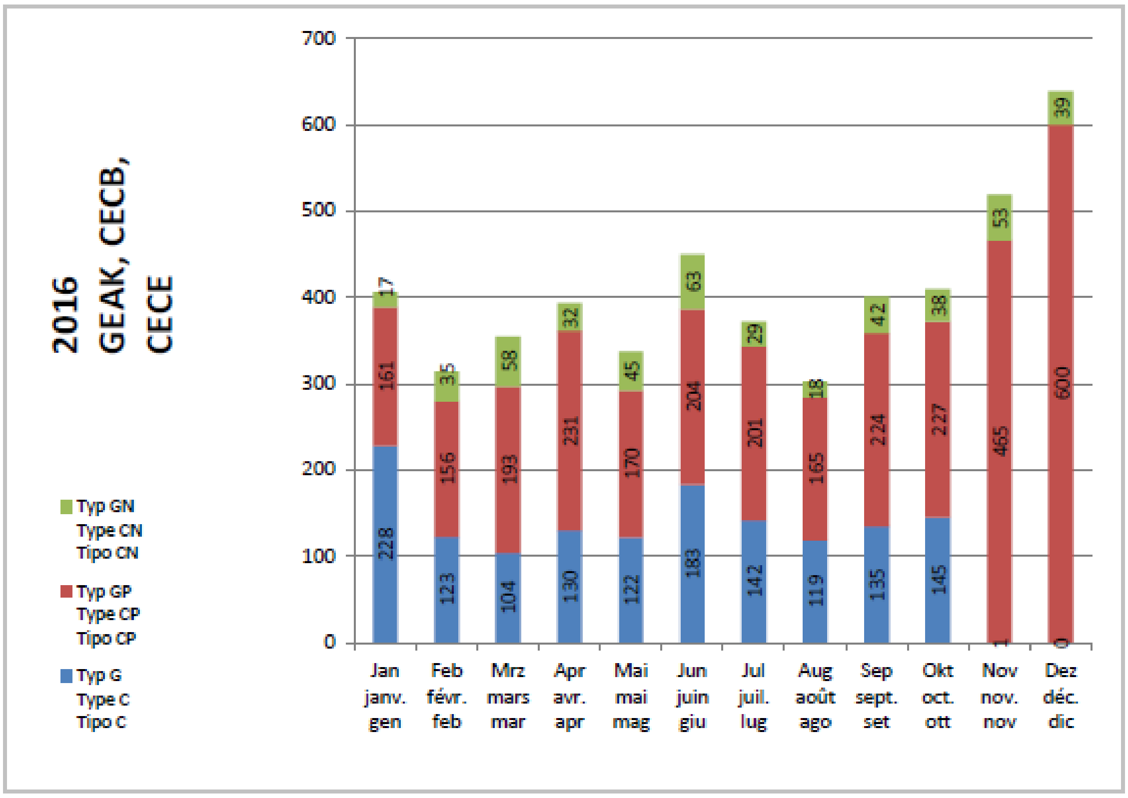


Figure 4: Distribution of CECB types published in 2016.

3.2.4 Available variables

The available data depends partially on the use of the building. The tool has different input templates for residential and non-residential buildings. A full table of the variables stored in the database is presented in the Appendix A, with each variable identified with a reference code. Reference codes 1 to 52 g in the table in Appendix A include values on the building envelope (U-values, surfaces, different factors for constructions elements against the ground or unheated spaces, g-values and shade coefficients for windows…), sometimes years and percentages of renovation (when an assistant or “Wizard” is used to propose some U-values). The HVAC data includes the type of heating installation (water und space heating) and the distribution (with its thermal insulation); these entries are found under code 53a to 59f. Code 60 to 60h describe variables related to electricity use (standardized set of household appliances; for example, lighting and electronic devices or other installations via demand-per-unit-area) as well as mechanical ventilation. Codes 61a through 61h give an overview of the results. Depending on the category of building, there might be some supplementary descriptive information as well, which are not relevant for the calculation (up to code 64).

The CECB tool offers also an economic evaluation of each retrofit option with data on the lifetime, prices and costs for energy, a description of all construction elements, and further parameters which all can be modified by the Expert. The results show how much a retrofit option would cost initially as well as in the future (typically looking at a time span of 25 years)

All input parameters (as well as most results) can be extracted from the database and thus made available for research purposes. As previously emphasized, the data sets are anonymized, according to the he privacy requirement of the building owners.

3.2.5 Quality control

Most existing buildings have electrical and heating consumption data available over several years. The Experts must request this data for a minimum of three years from the building owner and enter the data into the tool. This can help to cross-check numerical values and allows the Expert to adjust the calculated values of the final energy and heating demand. A range of +/- 15-20% is deemed acceptable.

It is important to note that the accuracy of the consumption data and any cross-checking are entirely under the Expert’s responsibility, neither the tool nor any authorities can or do check them.

These internal quality cross-checks alone do not guarantee sufficient quality of overall results. All results and assertions made by the expert on the certificate or in the report have to be consistent, plausible, and understandable not only for the authorities, but also for the client. The automatically generated consulting report made on the basis of all input data can and should be enriched or updated by the Expert (for example with further comments or analysis, more images, photographs or buildings schematics).

On a cantonal level, the authorities handling the CECB reports in the context of subsidy requests can reject a report considered bad or insufficient. A quality check program has been initiated in 2017 on a nationwide scale, not only to evaluate the quality of the certificates and documents generated, but also to help the Experts improve their knowledge and skills and/or make adjustments to the tool itself, where deemed necessary. More such programs will follow.

Within the tool, there are two important levels of quality control:

1. The calculation and validation made by the tool.
2. The inputs the expert made.

The calculation process was adapted for the first time after the official launch of the CECB at the end of May 2010 (Version 2). It was previously based on heating degree days (HDD), without correction for the altitude of the site and other details. This resulted in significant differences especially for buildings situated in the Swiss Midlands and higher altitude. For this reason, data extracts usually only include data from June 2010 onwards.

The calculator module for SIA 380/1 was verified when GP Datasets were first published in 2012. The examples used for the verifications complied with the requirements for certification of 380/1-softwares and proved that the calculator was valid, without providing any official certification per se.

The tool itself has in-built range-checking for most data. However, naturally these boundaries are fairly loose. Contradictory inputs will be highlighted to the Expert or messages will appear, and a final calculation can only be initiated after all input errors have been removed.

As for the input made by the Experts and the validation by the tool, there is an important step for all existing buildings: energy consumption data have to be collected over a period of at least three years of utilization and entered in the program as a validation measure. The tool will calculate and show the difference to theoretical consumption, allowing the Expert to adjust the parameters as needed. A difference below 15 - 20% is considered acceptable.

3.2.6 Data accessibility

All certification cases prepared by CECB Experts since 2009 are registered in a national database. This database of active (i.e. unpublished) certificates and already published certificates is fully accessible to CECB programmers and administrators. Experts see only their own cases (also referred to as their “portfolio”) and the public cannot access any of it but can check the validity of a known (their) certificate-number.

The data of a CECB is the property of the building owner and is not supposed to be shared. It is therefore mandatory to respect the anonymity of the data when used for research/statistic purposes. Data extracts for research purposes are therefore made available in an anonymized manner, i.e. without address, names or spatial information (EGID number= federal identifier) in general. If some identifying data are required, and the request does not originate from a Swiss canton, a Data Access Agreement is mandatory in order to protect the owner.

3.2.7 National Representativeness of the CECB

An important advantage of using this dataset is the large number of buildings and its geographical coverage of Switzerland as a whole. After having cleaned and filtered the data to obtain only residential buildings, it was tested whether the resulting sample was representative of the Swiss buildings stock. The National Register of Buildings, published by the Swiss Federal Statics Office (FSO, 2017), was used for comparison in order to check the representativeness of the CECB sample.

According to this National Register of Buildings, at the end of 2017, there were 1.7 million residential buildings in Switzerland. Of these, 57% were SFH and 26% MFH (FSO, 2017). These buildings account for 32% of Switzerland's final energy consumption, representing a total of 67 TWh/y including space heating, cooling, ventilation, domestic hot water, lighting, and general electricity consumption. The largest share of this energy consumption is devoted to space heating and domestic hot water, i.e. 55 TWh/y (Prognos, 2017), representing the focus of this study.

Figure 5 compares the heating system used in the buildings covered in the CECB sample, revealing an excellent match with the building stock. The small mismatch for direct electric heating (*Electric*) and heat pumps (*HP*) can be partially explained with an incorrect identification of the heating system by the CECB Experts (meaning by *Electric* the energy source and not the heating system), as discovered later in the analysis.

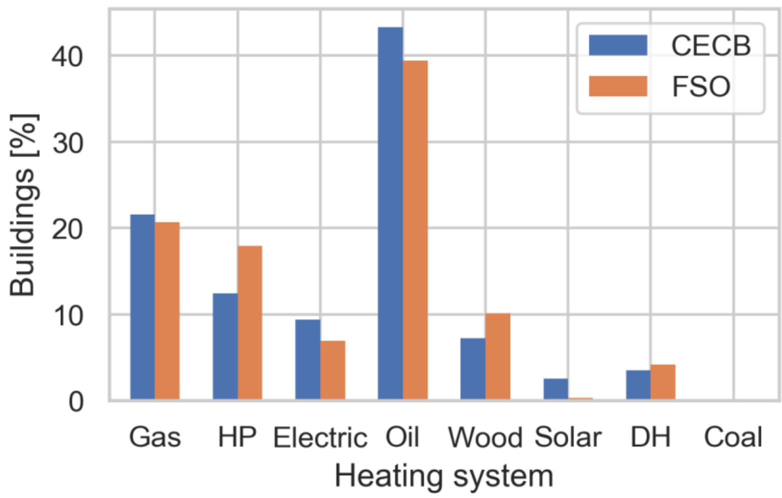


Figure 5: Heating system type distribution in residential buildings according to the Swiss Federal Statics Office (FSO in orange) and the CECB sample (blue), (Coal= 0.8%).

In Figure 6 the building construction period is compared, showing over-representation of the buildings constructed between 1945 and 1990. This can be partially explained by the original focus of the CECB on buildings in need of refurbishment (but which was less applicable to historic buildings pre-1945).

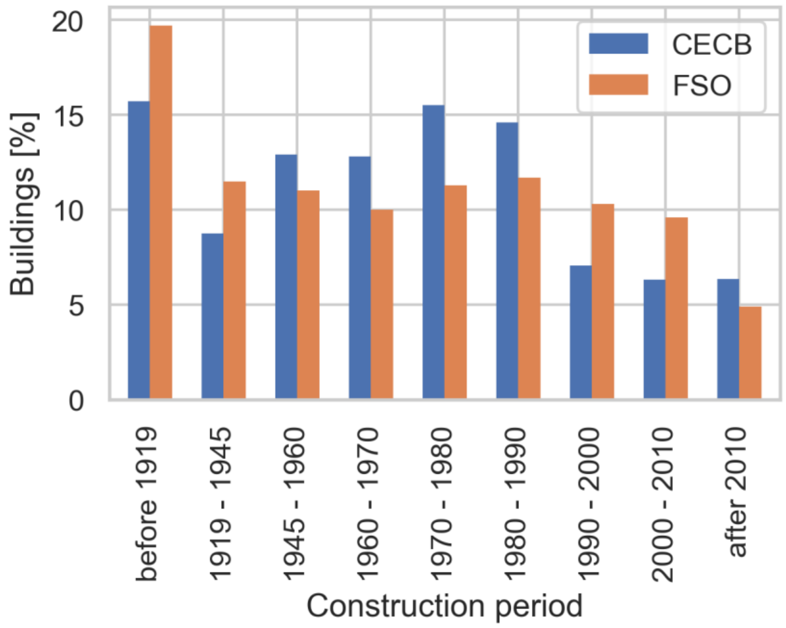


Figure 6: Comparison share of buildings as a function of the construction period between FSO (orange) and the CECB sample (blue).

The database was also investigated comparing the number of buildings per canton. In this case, some disparities were found between cantons, mostly due to differences in regulations. It is important to highlight that the regulatory situation is rapidly changing, which will affect the future evolution of the dataset. To conclude, despite some differences in representation between cantons, the CECB dataset used for this study can by and large be considered as representative for the Swiss residential building stock. Figure 7 shows age and energy label distribution of the CECB dataset. It is interesting to note that the majority of buildings built after 2010 still do not achieve the highest efficiency rating.

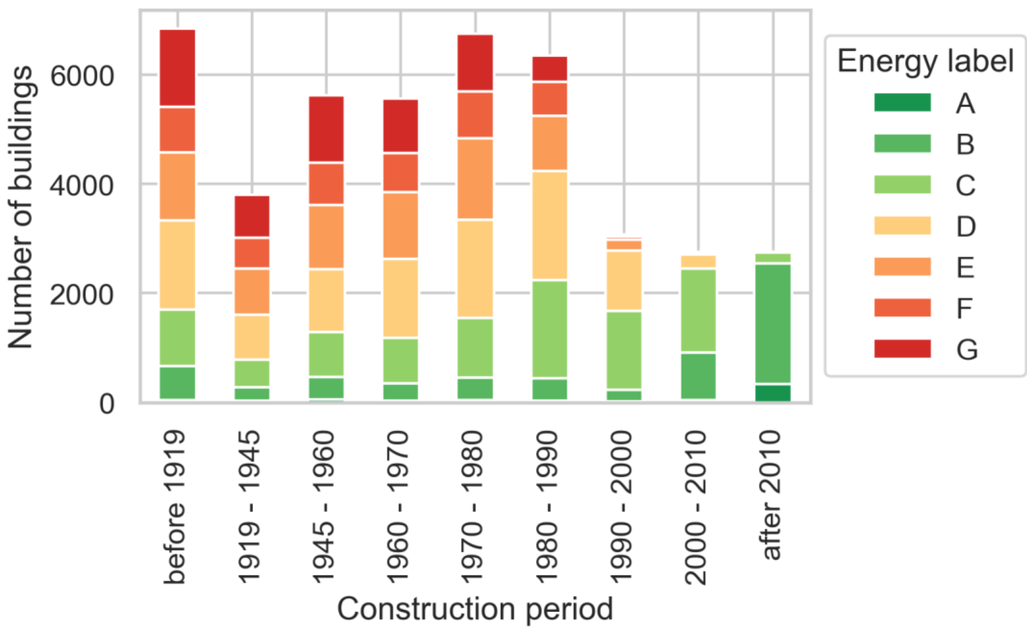


Figure 7: Energy label distribution in the CECB as a function of construction period.

Figure 8 shows the distribution of the number of buildings and the corresponding total energy reference area as function of the energy label in the CECB sample. The distributions are similar for the number of buildings and ERA, with the notable exception of F and G, for which there are more buildings relative to the ERA, indicating that these label categories are primarily found among smaller residences; to a lesser extent this also seems to be the case for labels B and E.

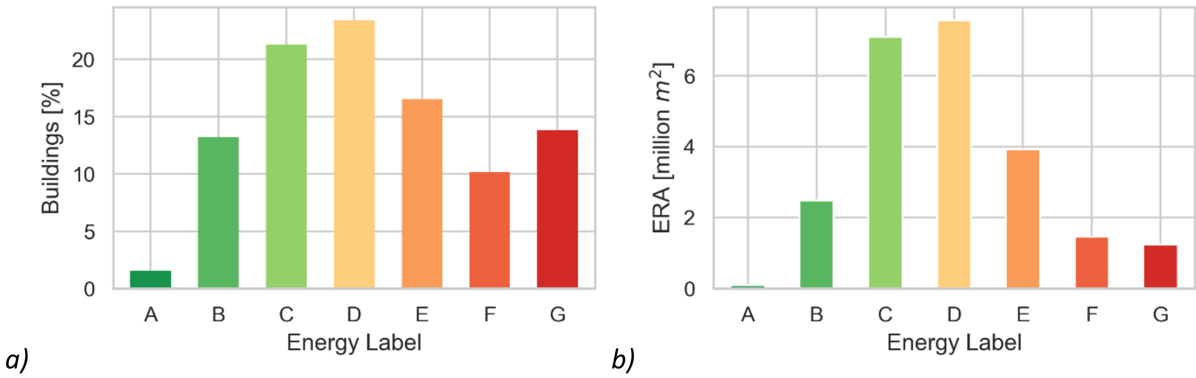


Figure 8: a) Energy label distribution by share of buildings and b) by energy reference area (both according to the CECB dataset).

The label G in Figure 8a does not follow the normal distribution expected from Figure 8b. This may be caused by the fact that this is the most heterogeneous group defined only by the minimum energy demand (i.e. no maximum demand) and therefore includes a large range of building performance levels.

3.3 Minergie

3.3.1 Minergie label

The Minergie online platform (Minergie, 2018a) is a database supporting the buildings certification activity of the Minergie Agency. The agencies are working together with the cantons to encourage the rational use of energy and the use of renewable energy as a contribution to reducing environmental impact while improving the quality of life.

The platform has two main functions: an administrative function (workflow management of the building certification process) and a statistical function (collection of information regarding the type of certified buildings and the main characteristics concerning the use of energy in certified buildings). The data quality is guaranteed by the Minergie Agency, the certification centre checks for the consistency of the data for each building. For each building at least the following variables are collected:

- Address, information on the project stakeholders.
- Communication between the Minergie certification centre and the applicant.
- Main information related to the building's theoretical energy consumption:
    - heat and/or cooling system
    - energy needs for heating, cooling, ventilation

- energy production from renewable sources
- energy indicators according to the Minergie standard.

The data contained in the platform is partially accessible to the general public through a search interface (Figure 9, Figure 10). Publicly available data includes the building address and type, heating type, surface area, and type and date of certificate award. Design energy consumption is not part of the public data. Detailed access to information exchanges through the platform is given to project stakeholders (building owners, Minergie agents, etc). Energy consumption data of buildings (calculated) are only visible for the Minergie Agency. It must be underlined that the calculations regarding the theoretical energy needs are provided in the certification process mostly in paper form. Only the main results are included in the Minergie database.

The online database contains all types of buildings that have obtained a Minergie certificate or are in the process of obtaining it. The database currently contains about 46 000 buildings corresponding to approximately 54 million square meters of Energy Reference Area, distributed across Switzerland (Figure 11). The database contains the calculated energy consumption of the buildings based on the inputs from the building planner. This consumption is used to show that the building meets the requirements to obtain the Minergie certification. The database also contains the communications between the building certification applicant and the certification centre.

Figure 9: Minergie online database search tool (minergie.ch).

Figure 10: Example Minergie Online Database public results for one building.

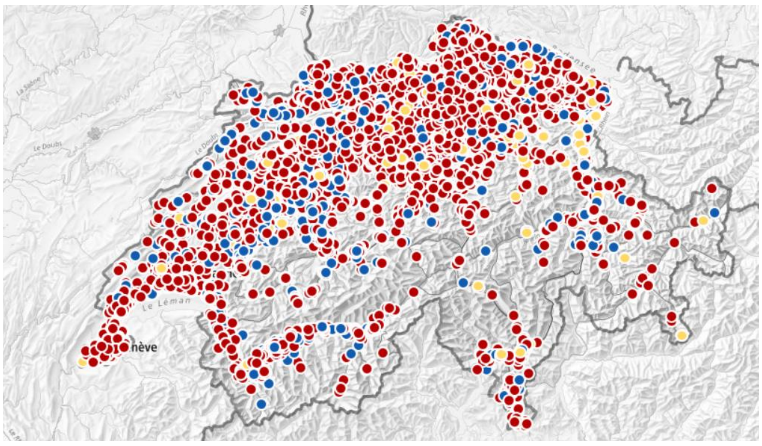


Figure 11: Map of the locations of Minergie certified buildings in Switzerland (Minergie, 2019).

It should be underlined that the data contained in this dataset are the result of theoretical calculations performed by designers in the certification phase. The energy consumption data are not collected by monitoring the building's energy use. The energy needs contained in the platform are calculated using standard calculation methods (SIA norm technical regulations) or monthly/hourly simulations. In addition, the calculations are based on the methods of the Minergie standard. These sometimes include the use of weighting factors that can favour or penalize different sources of energy (Minergie, 2018b). For this reason, the Minergie indices are not directly comparable with the expected theoretical final energy consumption of buildings. In the GAPxPLORE project, the analysis of the EPG for Minergie buildings is based on final energy consumption values excluding weighting factors.

The data used in the GAPxPLORE project were directly provided by the Minergie Agency in the form of excel tables. For the purpose of detailed analysis of the EPG of individual Minergie buildings (Section 7), the Minergie agency provided the original calculation documents produced during the certification phase.

3.3.2 Minergie dataset

A preliminary analysis was carried out on the Minergie database to get some first information on it. Figure 12 shows the distribution of the different standards. It can be seen that almost 90% of the buildings are "normal" Minergie, about 9% are Minergie-P and only 1% is labelled Minergie-A.

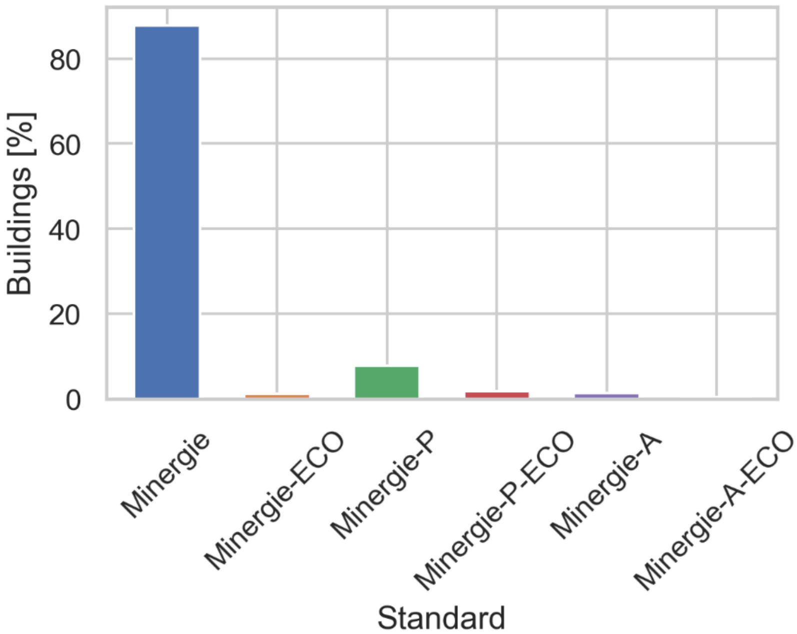


Figure 12: Standard distribution in the Minergie database.

In addition, the different destinations of use were also studied, to understand which kind of buildings were contained in the database. As can be seen in Figure 13, almost 90% of the certified buildings are residential (SFH and MFH).

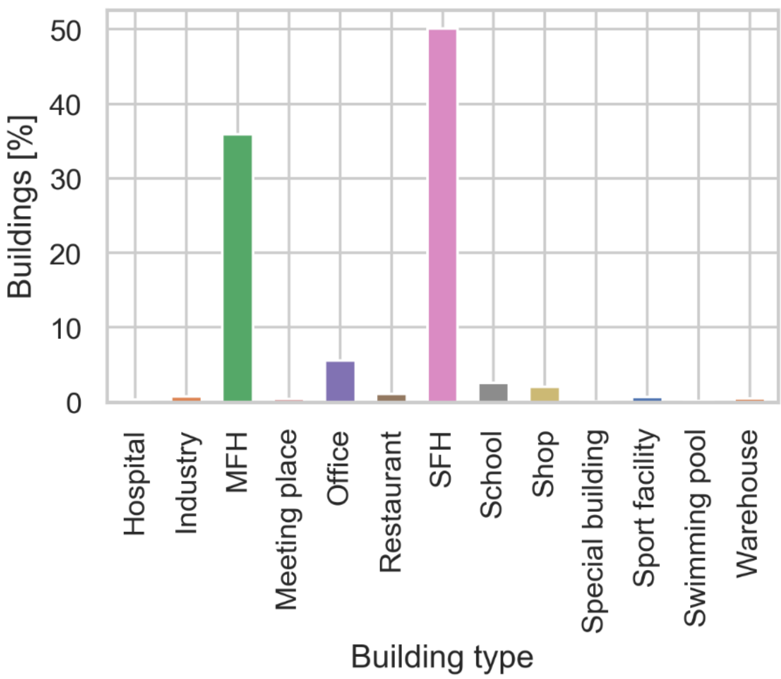


Figure 13: Destination of use distribution in the Minergie database.

Finally, it was checked how these buildings were distributed throughout the territory, so as to understand if all cantons were represented. Figure 14 compares the number of buildings per canton.

In orange the buildings from the National Register of Buildings (FSO, 2017) and in blue the building Minergie are reported.

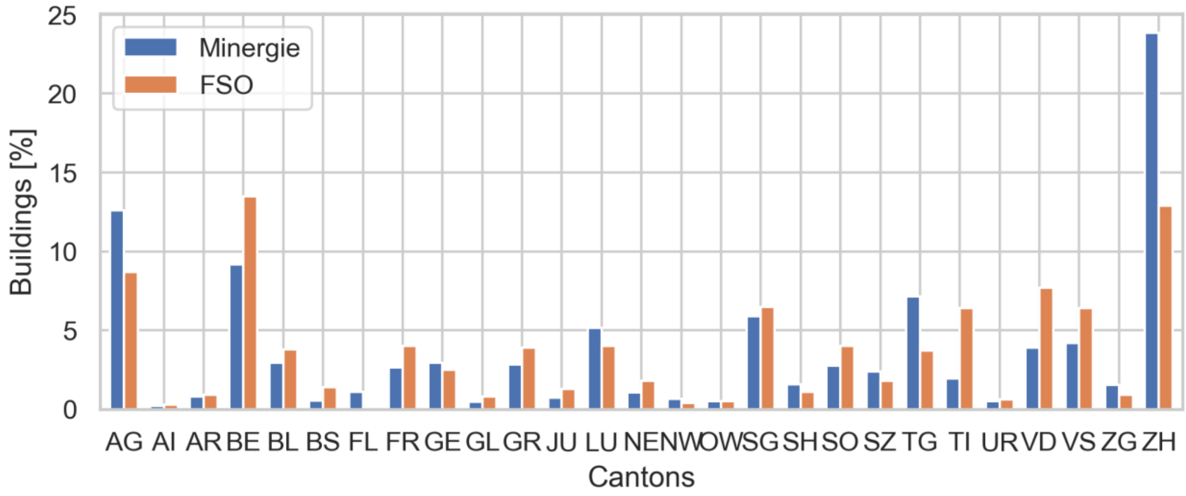


Figure 14: Comparison between FSO (orange) and the Minergie (blue) in function of the cantons.

Some disparities are evident between cantons. For example, the cantons of Zurich (ZH) or Aargau (AG) are both very well represented in the Minergie database. By contrast, the cantons of Bern (BE) or Ticino (TC), are poorly represented.

3.4 Energo

The Energo online database includes about 8 000 buildings (Energo, 2018). The Energo association, which is part of the SwissEnergy program (Federal Office of Energy), is a leading competence centre for energy efficiency in Switzerland. The Energo association signs contracts with building owners on energy efficiency improvement of their building. An Energo engineer then optimizes the building's heating system and electricity use. The goal is to achieve at least 10% energy savings without significant costs. This has been a successful program (on January 11th 2018 the Federal Office of Energy awarded Energo with the Watt d'Or prize for its participation in the Eco21 program of the Geneva's energy utility SIG).

Typically, the Energo platform includes large existing buildings with high energy consumption. For the most part these are hospitals, old people's homes, administrative buildings, or large residential buildings. Most of the buildings contained in the platform are old buildings, but new buildings have been added in recent years as a consequence of new contracts that provide the energy optimization of new buildings. It has been observed by the Energo Association that Swiss buildings consume more energy than expected, i.e. the high energy use is often a reason for building owners or managing companies to join the Energo platform. For each building the consistency of the data collected is checked by an engineer. In addition, the Energo association checks the consistency of the energy monitoring.

As basis for implementing energy efficiency measures and to demonstrate the savings achieved, buildings are monitored by collecting consumption data on a weekly basis. This data is collected by the building maintenance staff (concierge, technical staff etc.) or by smart meters and it is then entered in the data base. Consumption data are collected from all buildings meters monitoring the consumption of heat, electricity and water. The energy monitoring system generates graphs, indicators and trend consumptions for each building. In this way, it is possible to visualize consumption on annual, monthly or weekly basis for each building in the platform. The optimization measures performed by the engineer are also listed. For each building it is possible to estimate the energy savings (with climatic correction) achieved by the engineer.

Data is stored on the Energo database through an online platform (called Energotools). Data access is granted to the building owner, to the engineer who optimizes the building, to the building operator and to Energo. Examples of the display and user interface that is used to track the building performance are shown in Figure 15, Figure 16, Figure 17, Figure 18, and Figure 19, kindly provided by Energo.

On the one hand, the data is used for energy efficiency improvement and on the other for the purpose of a real estate portfolio energy management for Cantons (e.g. Fribourg, Geneva, Ticino), municipalities (Montreux, Nyon) or private owners. The data of Energo database can be also used for statistical purposes (determination of average consumption for different categories and sizes of buildings) or to analyse individual buildings. The analysis of individual buildings is based on data the building's heating system and the monitoring concept.

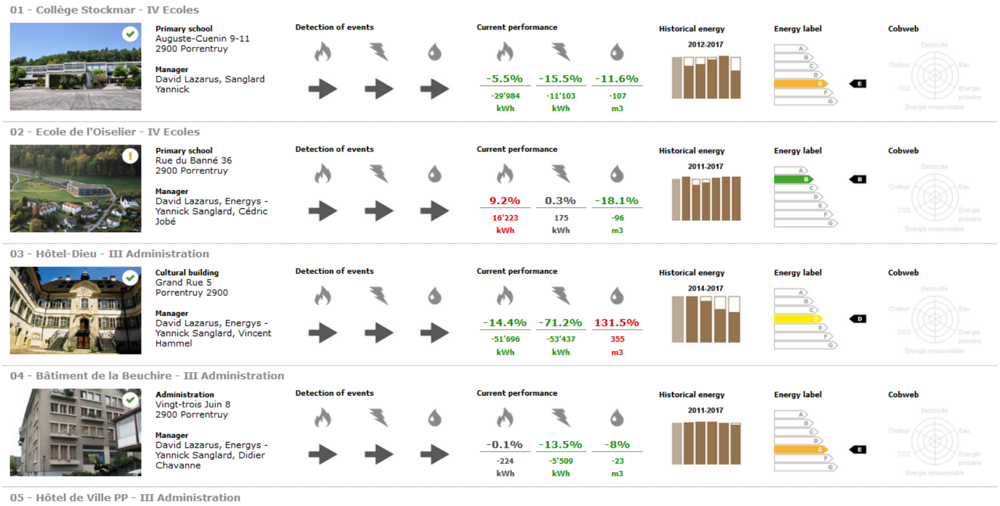


Figure 15: Exemplary list of buildings in the Energo platform.

CA/EL/ACQUA - Prospetto annuale

Start Date		Elettricità			Calore			Acqua		Temperature
10.09.2011	Ref.	Real	Eco	Ref.	Real	Eco	Ref.	Real	Eco	
	[kWh]	[kWh]	[%]	[kWh]	[kWh]	[%]	[m3]	[m3]	[%]	[°C]
10.09.2011	296'825	300'470	-1.23	367'474	366'327	0.31	1'652	1'668	-0.97	11.56
10.09.2012	296'483	312'017	-5.24	379'430	348'991	8.02	1'657	1'733	-4.58	11.08
10.09.2013	296'033	266'485	9.98	328'780	218'860	33.43	1'648	1'543	6.36	11.54
10.09.2014	295'019	316'633	-7.33	308'894	175'801	43.09	1'627	2'183	-34.16	12.58
10.09.2015	296'863	293'265	1.21	354'318	189'524	46.51	1'653	1'858	-12.42	11.52

Figure 16. Example of the annual consumption of heat, electricity and water. Energy savings in green.

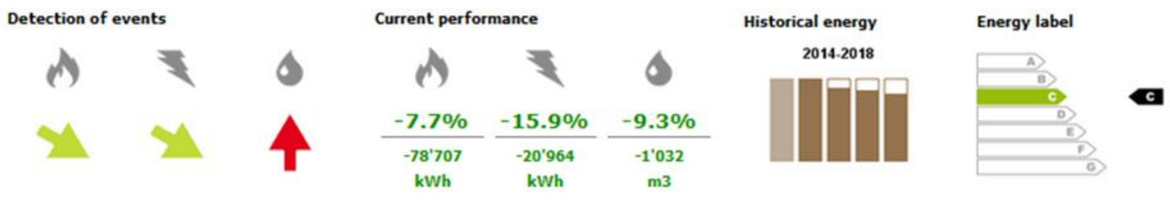


Figure 17: Example of Energo Energy Panel and analysis of the consumption of the building.

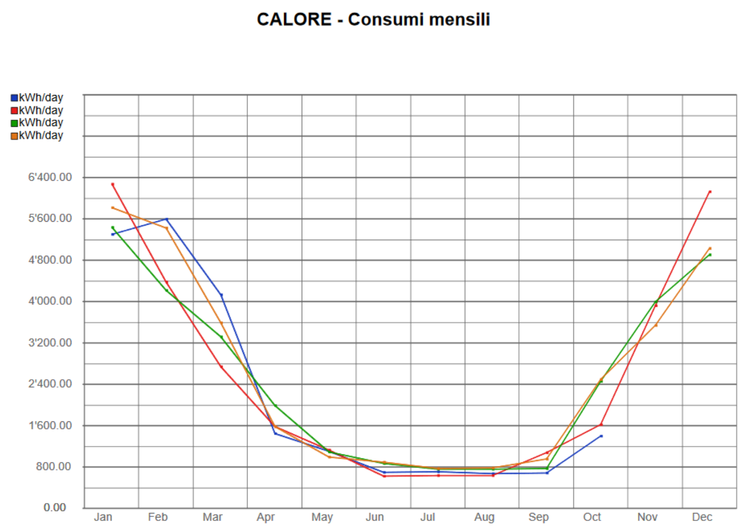


Figure 18: Example of monthly analysis of building consumption.

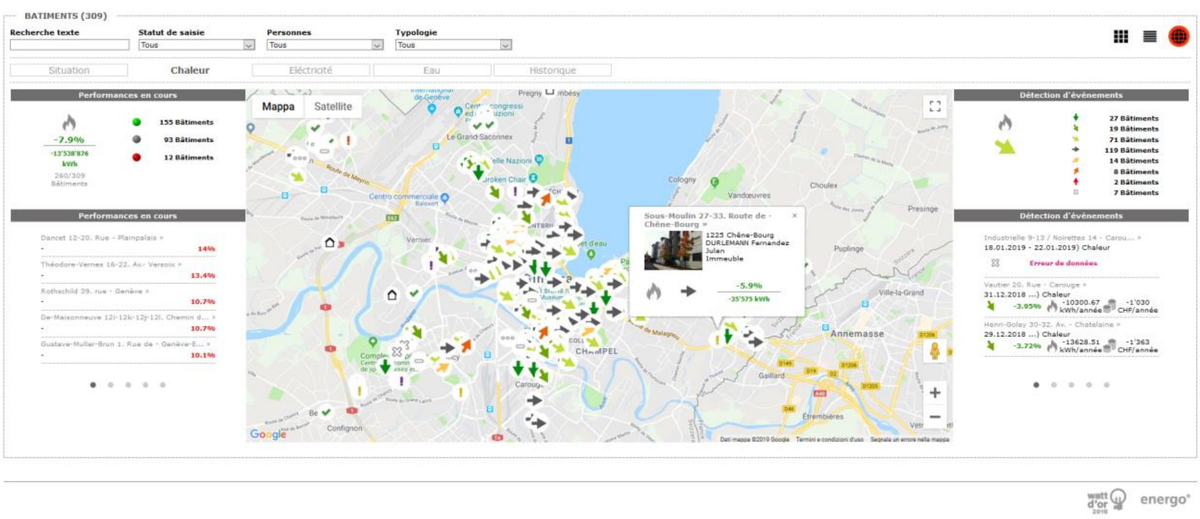


Figure 19: Example building consumption monitoring in Geneva in real time (Eco 21 program).

3.5 Swiss Solar Agency

Since 1991 the Swiss Solar Agency is awarding prizes to buildings with exemplary solar installations and energy balances. Until November 2018 a total of 3 564 applications were reviewed by the Swiss Solar prize Jury consisting of engineers, architects, academics and others. Since 2010 a collaboration has been developed with the renowned British architect Norman Foster and about 20 technical universities. To receive the award, buildings are expected to meet energy efficient Minergie-P /Passivhaus standards with high levels of thermal insulation (max U-values of 0.09 to 0.11 W/m^2K). Additionally, buildings should feature aesthetically exemplary and fully integrated solar photovoltaic or solar thermal roofs and/or facades. The amount of energy provided by these solar installations should exceed the net energy demand of the buildings (resulting in CO_2-free energy surplus), also referred to as net-positive energy buildings (NPEB; "PlusEnergyBuildings"). Finally, the use of this energy surplus to power emission-free transportation (e.g. through charging stations for electric vehicles) is encouraged.

In order to evaluate the buildings' energy performance, paper application forms containing various pieces of information about the applicants' buildings including their solar and thermal installations were developed by the Swiss Solar Agency. For application to the Swiss Solar Prize, these forms, pictures of the buildings and their solar installations, and a confirmation of electricity consumption provided by the energy utility as well as electricity feed-in from PV systems (generally covering a period of several months) must be handed in to the Swiss Solar Agency until 15th of April. The application forms are usually filled in by the landlord and/or their architects.

Since 2012 the Swiss Solar Prize Jury fills in an additional form with the verified and - if necessary - corrected data on energy consumption (based on information received from the energy utilities, energy bills). The owners of the buildings awarded with the Swiss Solar Prize have to submit revised, up-to-date confirmations of their net electricity consumption (net of consumption and re-injection in the grid).

This energy data is not systematically collected for one full year. For the purpose of the Swiss Solar prize, the values are scaled to estimate yearly consumption and the results are used to cross-check and confirm the building's predicted energy consumption. The confirmed scaled values are finally published in the annual Swiss Solar prize booklets.

For the purpose of the GAPxPLORE study, the following data were manually copied from the application forms (which were received in printed form) into an Excel spreadsheet, thereby covering Swiss Solar prizes between 2010 and 2018:

- Information about the building location (address)
- Type of building (single family house, apartment building, industrial building, etc.)
- Energy labels/certifications, if available (Minergie-P, passive house or similar building standards)
- Year of construction
- Energy Reference Area
- Presence of mechanical comfort ventilation
- Information about the building insulation (U-values of windows, wall insulation, etc.)
- Calculated energy consumption (with distinction by space heating, domestic hot water, and other electricity use where available)
- Measured energy consumption as reported in the Solar Prize Publication (i.e. scaled to one year)

- Measured energy consumption as reported by the building owners (i.e. not scaled), based on a variable number of days of monitoring together with the dates of the monitoring period (with breakdown by space heating, domestic hot water, and other electricity use, where available).

It should be noted that the information provided on the building insulation does not amount to a detailed design-level summary of the building fabric, i.e. it was not possible to calculate theoretical energy demand using by applying standard methods to the data provided for the Solar Prize.

4 Energy Performance Gap in the existing building stock

4.1 Introduction

This section studies the Energy Performance Gap in the Swiss building stock through the CECB database. The database, containing more than 50 000 buildings, and has been already proven to be representative of the residential stock in the section 3.2.7 and in previous study (Streicher et al., 2018). This exploratory analysis is providing robust, statistically significant results, pinpointing the subsets in which the EPG is the largest, mainly through the use of the CECB energy label. The large size of the data sample is crucial, since it allowed to arrive at representative results of high significance in spite of the relatively short time series. A drawback of this data is the limited number of newly constructed buildings with very high energy performance, which are however addressed specifically in Section 6. Namely, many studies have shown that such buildings tend to consume more than their theoretical consumption, which is the opposite of the finding in older buildings. In order to provide comprehensive guidelines, it was important to first understand the energy behaviour of the Swiss building stock, and only later extend the EPG analysis beyond the CECB data and focus on high performance building (Section 6).

4.2 Method and Data

4.2.1 Method

To calculate the EPG, Equation 1 (as introduced in section 1.1) is applied by using the values for the actual and theoretical energy consumption from the CECB described above (section 3.2). The performance gap analysed in this work is based on the difference between the real energy consumption and the theoretical energy consumption according to regulations assuming normalised operating conditions as set out in the national standards (Van Dronkelaar et al., 2016).

In order to compare the actual consumption on an equal basis, all the different energy carriers used (e.g. m^3 of gas, litres of oil, kg of biomass) are converted to kWh/(m^2y) of final energy using standard conversion factors (SIA, 2016a; Wesselmann, 2017). As already mentioned, this work only considers the final energy consumption for thermal use (space heating and domestic hot water) which is directly comparable to the actual final energy consumption for thermal use provided by energy bills.

To establish the difference between actual and calculated emissions, the CO_2 emissions of the CECB are calculated using the KBOB energy emissions intensity database, based on the Ecoinvent methodology (KBOB, 2016).

4.2.2 CECB dataset

Given the diversity of information contained in the original CECB dataset and their heterogeneity in terms of level of detail and accuracy of the inspection, pre-processing of the data was needed before proceeding with any analysis. There were 51 318 residential buildings (both SFH and MFH) in the original dataset. Any certificate with corrupted information was deleted, e.g. impossibly small heated area (< 1 m^2) or negative U-value for the envelope. Since some certificates had undergone several revisions, with all revisions stored in the dataset, only the latest version was kept as in most cases the previous versions were temporary incomplete copies created by the CECB Expert. After these operations the dataset was reduced to 43 639 buildings (85% of the initial dataset).

Similar filtering operations with comparable error ratio were found in several publications dealing with national energy data, as the SHAERE database (Social Rental Sector Audit and Evaluation of Energy Saving Results) in Van den Brom et al. (2017a), the VEA database (Flemish Energy Agency) in Delghust *et al.* (2015) and the CBS database (Statistics Netherlands) used by Majcen et al. (2013b).

Only the certificates with complete information on actual and theoretical consumption were retained, as in many cases the actual consumption was missing due to the lack of three years of energy bills. This requirement reduced the sample to 36 299 buildings. Finally, the outliers in the energy consumption were removed. Outliers in this case are buildings with energy consumption values which are extremely different from other buildings and which were hence considered to be highly atypical buildings or possibly erroneous data. To identify them, the modified Z-scores method was used as proposed by Iglewicz and Hoaglin (1993) with a score threshold of 50. This last filtering operation reduced the sample to the final size of 34 816 residential buildings (68% of the initial dataset).

4.3 Results and Discussion

4.3.1 Energy consumption difference

For the final sample consisting of 34 816 residential buildings with CECB, total actual final energy consumption for thermal use adds up to 2.77 TWh/y while the total theoretical consumption equals 2.95 TWh/y. Actual final energy use is therefore by 0.18 TWh/y or 6% lower than the theoretical consumption. The detailed results of aggregate and median consumptions as a function of the energy labels are presented in Table 7.

Table 7: Theoretical and actual final energy consumption in the CECB sample – total and median values by energy label.

Energy label*	No. Buildings	ERA [km²]	Total Theoretical Consumption [GWh/y]	Total Actual Consumption [GWh/y]	Median Theoretical Consumption [kWh/(m²y)]	Median Actual Consumption [kWh/(m²y)]
A	156	0.10	3.34	3.20	39.4	37.1
B	2554	2.55	123	148	41.9	50.2
C	7395	7.15	590	671	78.9	84.5
D	9067	7.64	904	928	121	116
E	6564	3.96	646	569	164	137
F	4039	1.48	301	231	202	151
G	5041	1.28	381	217	308	174
All	**34816**	**24.2**	**2950**	**2770**	**128**	**113**

** The energy label is attributed using the weighted final energy.*

The median values are indicative of the typical consumption of a building with that energy label. Figure 20 illustrates the total actual (in orange) and theoretical (in blue) consumption by energy label (totals according to Table 7). The figure clearly displays the different weights of the energy ratings in energy consumption, with "central" labels C, D, and E dominating total energy consumption (73% of the total). The pattern displayed in Figure 20 is determined by both the very different ERA distribution (Figure 8b and Table 7) and the average energy consumption per label (in kWh/m^{2}y, Table 7).

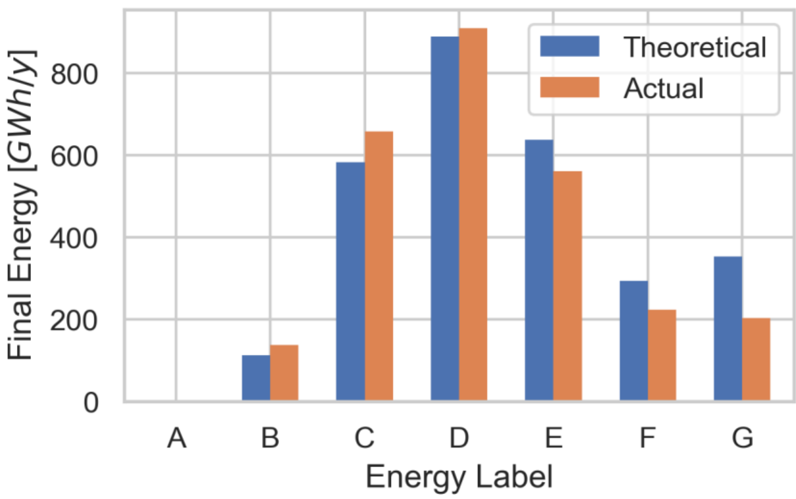


Figure 20: Sum of building energy consumption as a function of energy label (A-Theoretical: 3.3; A-Actual:3.2).

F and G labels jointly account for 23% of total consumption. Buildings with these energy labels consume far less energy than expected while the differences are relatively limited for the other labels. Energy retrofitting only F and G labelled buildings would therefore not be sufficient in order to reach ambitious energy saving targets. At the same time, deep energy retrofitting of buildings with an E, D and especially a C label is more difficult to justify, considering that these are consuming less energy per square meter and the payback times of the investments can be expected to be longer than for buildings with an F or G label.

The previous analysis was repeated for normalized final energy consumption per square metre of dwelling. Figure 21 shows the comparison between theoretical and actual consumption as a function of the energy label. As expected, the theoretical consumption is steadily decreasing with the improvement of the energy performance of the building. The actual consumption behaves quite differently, showing only little difference in energy consumption for the low ratings (E, F, and G labels) and a substantial reduction similar to the theoretical one for better ratings (A, B, C, and D labels). This once more suggests that an advancement from an energy label G to F or E would not deliver the expected improvement and that it is instead necessary to reach at least a label D to achieve significant actual energy savings. This aspect is particularly relevant when public subsidies for energy retrofit are related to the number of label steps taken.

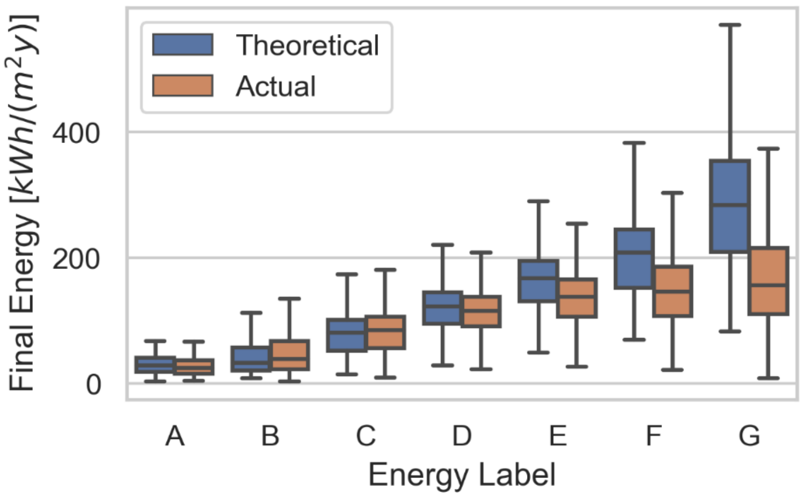


Figure 21: Theoretical and Actual consumption per energy label.

Figure 21 furthermore shows that buildings with low performance (G, F, and E labels) consume very substantially to moderately less than predicted. Vice versa, buildings with higher performance (B and C) consume marginally more than predicted. This result supports previous finding in the literature (Delghust et al., 2015; Majcen et al., 2013; Merzkirch et al., 2014; Ramallo-González, 2013; Raynaud, 2014; Sharpe and Shearer, 2013). A-label buildings appear to consume slightly more than predicted, this is further discussed in the following section. Furthermore, it needs to be emphasised that overall the absolute difference between theoretical and actual energy consumption remains small for all labels A to D.

4.3.2 Energy Performance Gap

The energy consumption difference in the building sample highlighted in section 4.3.1 is caused by the existence of a significant EPG per building. In this work, the median EPG was found to be -11% (Equation 1), implying that actual consumption was clearly lower than theoretical consumption. This EPG value is not equal to the difference in energy consumption across the sample (-6%, see section 4.1) due to weighting of the EPG values per building with the respective ERAs and the specific energy consumption per meter square.

Figure 22 expresses the difference between theoretical and actual consumption in terms of EPG (Equation 1). The EPG shifts from a large negative value to a relatively moderate positive one as the energy rating improves (with the exception of label A, see below). That is to say, the buildings go from consuming less than expected (negative EPG) to consuming more than expected (positive EPG for label B). It is also important to note that there is a large spread between the minimum and maximum values for every label.

The trend for A-label buildings is less clear. Although many buildings showed a positive EPG the median was negative, which could support the theory that the most efficient buildings are more robust to the EPG (Feist et al., 2003; Peper and Feist, 2015). However, the results concerning the A-label buildings should be treated with caution, as these buildings were poorly represented in the sample: only 156 buildings with A-label were present in the dataset, equal to the 0.5% of the total sample.

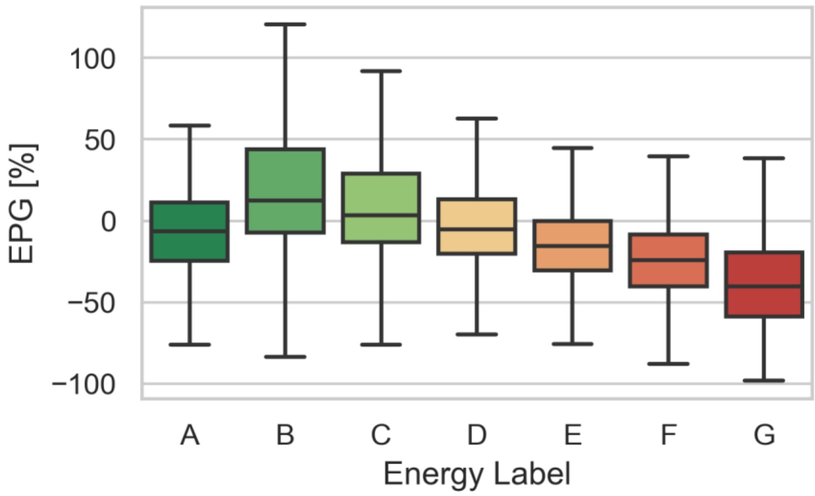


Figure 22: Energy performance gap per energy label.

It is important to note the minimum and maximum values in Figure 22, which show that the energy consumption of some buildings is actually very different than expected. This spread of values also demonstrates that there is a strong overlap in energy use across the ratings. This means that using only the energy rating as predictor of actual energy consumption is subject to high uncertainty. Using theoretical consumption values as proxy for real performance entails the risk of incorrect assessment, e.g. as the result of discrepancies in operating conditions, malfunctioning of technical systems, and the neglect of a range of loads (e.g. plug loads). Such a rough approach should be used in policy making only to evaluate the entire national building stock (here, the extremes can be expected to balance out). However, it should be kept in mind not to use these theoretical calculations as reference values for actual results (as pointed out by Burman, Mumovic and Kimpian, 2014).

Table 8 gives the median values of the EPG for each energy label. When interpreting these values and likewise Figure 22, it should be taken into account that, across the labels, one percent point represents very different energy consumption values in terms of kWh/(m^{2}y). For example, in label E an EPG of -15% corresponds to a difference between actual and theoretical of -27 kWh/(m^{2}y), while in label B, a similar EPG with inverse sign, +12%, corresponds to an absolute difference of only +8 kWh/(m^{2}y). These values are smaller than those reported in existing case studies in Switzerland (Khoury et al., 2018; Thaler and Kellenberger, 2017), most likely because this is the first stock-level assessment (rather than focusing on small numbers of high efficiency buildings).

Table 8: Energy performance gap per energy label.

Energy label	Median EPG [%]
A	-6.19
B	12.5
C	3.57
D	-5.22
E	-15.4
F	-24.3
G	-40.4

Figure 23 shows that a similar pattern as displayed in Figure 21 is also found across the construction periods: for old buildings actual consumption is lower than theoretical consumption (negative EPG), while buildings built after the year 2000 are consuming somewhat more than expected (positive EPG).

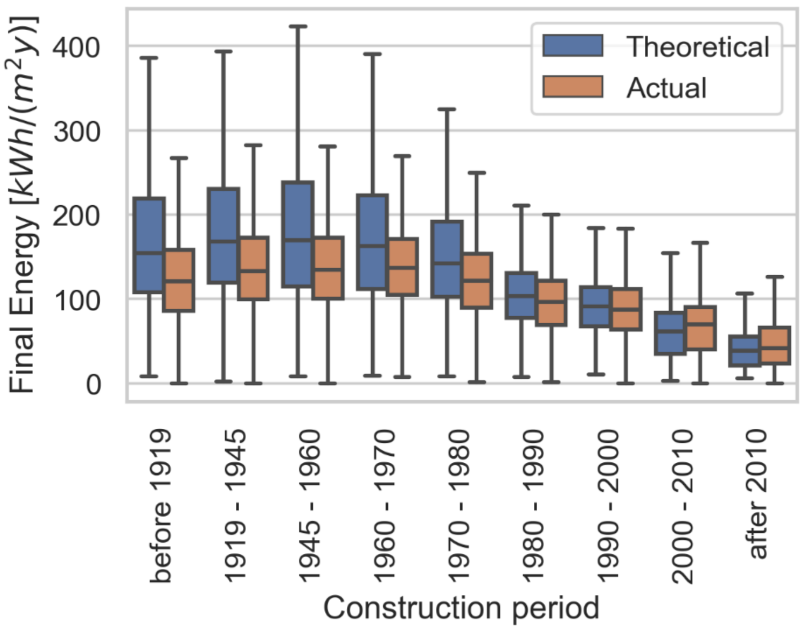


Figure 23: Theoretical and Actual consumption per construction period.

It should be noted that the values close to zero in Figure 23 are always positive even if small, and that manual inspection of a selection of these cases did not reveal any clear data corruption or other markers that the record was invalid. A possible explanation is that some buildings are from the same construction period but have been retrofitted, and therefore presenting a lower energy consumption than other buildings of that period. Nevertheless, the graph confirms that old and less performing buildings consume significantly less energy than expected.

As mentioned above, the attention should not be limited exclusively to older buildings with a lower energy rating (labels F and G), which contribute only to a limited extent to actual consumption as they are currently performing better than expected and as they have a relatively small ERA (see Figure 8, Figure 20, and Table 7). An effective energy policy should instead include the buildings in the middle rating (labels D and E), which contribute substantially to the total actual consumption thanks to their greater ERA.

These findings may partly also explain the so-called rebound effect according to which, after a building retrofit, only a portion of the energy reductions estimated are achieved in practice due to changes in occupant behaviour (Druckman et al., 2011). In existing literature (Galvin, 2014; Haas and Biermayr, 2000), savings are often calculated using a mix of theoretical and actual consumption data, therefore the observed EPG between theoretical and actual consumption (independent of energy retrofit) could explain part of this difference between expected and achieved savings.

However, it once more needs to be noted that the EPG (in % terms) for C-label buildings is very small, that the somewhat larger EPG for B-label buildings (Figure 22) translates to a small EPG in specific energy terms (between 6 and 8 kWh/(m^2y) for label B and C according to Table 7) and that the EPG for A-label buildings is even negative (Figure 22).

4.3.3 CO_2 emissions per label category

Similar analyses to those carried out on energy were also performed for the CO_2 emissions. Table 9 presents the aggregate total theoretical and actual CO_2 emissions per energy label, as well as the respective median values.

Table 9: Theoretical and actual CO_2 emissions in the CECB sample – total and median values by energy label.

Energy label	No. Buildings	ERA [km^2]	Total Theoretical CO_2 Emissions [kt CO_2-eq/y]	Total Actual CO_2 Emissions [kt CO_2-eq /y]	Median Theoretical CO_2 Emissions [kg CO_2-eq/(m^2y)]	Median Actual CO_2 Emissions [kg CO_2-eq /(m^2y)]
A	156	0.10	0.42	0.37	5.02	4.87
B	2554	2.55	17.8	22.1	5.95	7.43
C	7395	7.15	131	149	16.6	18.0
D	9067	7.64	237	243	30.4	29.3
E	6564	3.96	173	152	41.8	35.2
F	4039	1.48	78.7	60.1	50.3	37.6
G	5041	1.28	90.5	51.7	68.7	39.4
All	**34816**	**24.2**	**728**	**678**	**30.1**	**27.9**

Figure 24 shows the total actual and theoretical CO_2 emissions per energy label, to better highlight the weight of each energy label on the overall CO_2 emissions. These closely follow the pattern for total energy consumption shown in Figure 20. As for the energy consumption, the main contributors to CO_2 emissions are the buildings in the C, D and E labels. The contribution of B-labels is very small, partly due to their small total ERA (Figure 8), while the single A-label building remains invisible on this scale. A further important reason for the very low representation of A and B label buildings is that they use a much smaller or even negligible share of fossil fuels (see Figure 25).

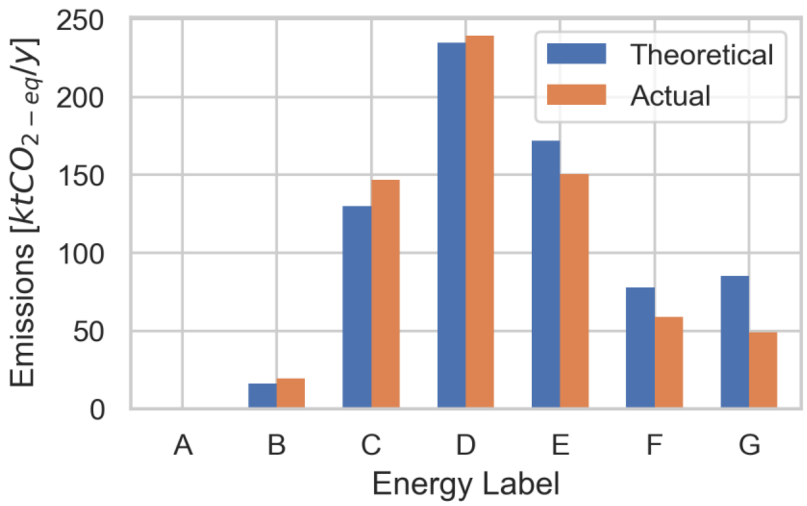


Figure 24: CO_2 emissions as a function of energy label (A-Theoretical: 0.42; A-Actual:0.37).

The similarity between Figure 20 (energy) and Figure 24 (CO_2 emissions) is very interesting. A much larger contribution to CO_2 emissions would have been expected, for the same amount of energy consumed, from old buildings with worse energy ratings due to their arguably inefficient and polluting heating systems. This effect is attenuated by the installation of new heating systems in old building[2]. On the other hand, the homogeneity of emissions suggests that the heating systems used in medium rating buildings (labels C, D, E) are not substantially different from those used in the lower rating (labels F, G). This is confirmed by the analyses shown in the Figure 25, where the heating systems are presented as a function of the energy label.

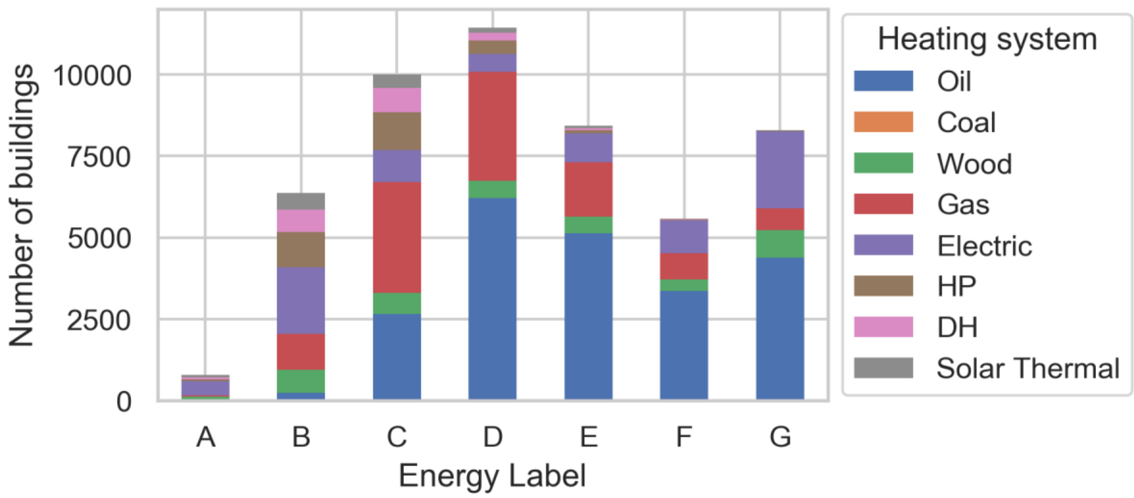


Figure 25: Heating system distribution in function of energy label.

[2] A supplementary analysis of the CECB dataset on the installation periods of the heating systems showed that most old buildings are equipped with new boilers, but still powered by fossil fuels (74% of all the heating system installed after 1990 in buildings constructed before that year are gas- and oil-fuelled).

As shown in the Figure 25, the mix of technologies and fuels used in labels C to G is not very different and the presence of oil and gas boiler is predominant in these categories, leading to very similar carbon content of the energy supply for these labels of around 0.23 kg CO_2-eq/kWh. In contrast, the absence of oil boilers in buildings with labels A and B brings their carbon content to about 0.12 kg CO_2-eq/kWh.

The results of CO_2 emissions per metre square of ERA (Figure 26) are determined by both annual energy consumption per m^2 as a function of energy label and the change in energy mix (increasing shares of gas at the expense of oil from label G to C and growing shares of heat pumps from E to B). Similar to the energy consumption, the actual CO_2 emissions in lower performing buildings are found to be smaller than the theoretical ones. The graph also shows that the CO_2 emissions are reduced by almost a third when moving from C to B label, a reduction which is notably more pronounced than for energy consumption (Figure 21) revealing the high efficiency and low CO_2 intensity of the heating systems installed in new or deeply renovated buildings.

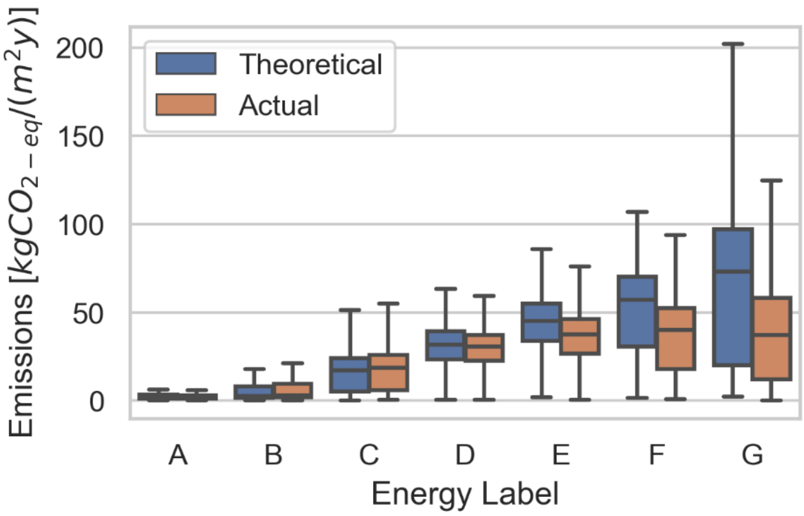


Figure 26: Theoretical and Actual CO_2 emissions per energy label.

4.4 Conclusions

This task has investigated the Energy Performance Gap, defined as the difference between theoretical and actual energy consumption of a building, in the residential sector. The work was based on the official database of the Cantonal Energy Certificate for Buildings that contains data of almost 50 000 buildings, making this study the most comprehensive so far conducted in Switzerland and one of the largest in Europe. The CECB reports the energy efficiency of the building, distinguished into classes A to G by means of an energy label, the actual consumption by the energy bills, and the building's energy requirements according to Swiss standards. Using this information the EPG was quantified for final energy use and CO_2 emissions related to the supply of space heating and domestic hot water.

The analyses revealed the existence of an EPG for residential buildings, with a median of -11% per building. This implies that the actual consumption of final energy is 6% lower than predicted for the entire residential stock. This is due to the large share of buildings with lower energy rating (label E-G) which were found to perform significantly better than predicted. A strong correlation was found between energy label and EPG. For low performing G-labelled buildings, a negative EPG of -40% was determined, while for the higher performing buildings with B-label a positive EPG of +12% was determined. These results imply that higher performance buildings are consuming somewhat more than predicted while lower performance buildings are consuming significantly less than predicted. However, the limited number of A-label buildings in the CECB dataset and the absence of very high-performance buildings (e.g. Minergie) calls for further investigations (Section 6).

A similar pattern to the EPG as a function of the energy labels was found for CO_2 emissions. An important finding is that the actual emissions in terms of kg CO_2-eq/kWh are very similar between the labels C and G, showing a large drop only for the labels A and B which is not matched by an equally large drop in energy consumption. This highlights the contribution of the high efficiency and low emissions of the heating systems installed in these new or deeply renovated buildings, and further indicates a need for energy policy to incentivise reducing carbon emissions in addition to requiring a minimum level of energy efficiency.

This research suggests that while policy makers should encourage energy retrofitting to reach the ambitious targets of the national energy strategy, a good strategy should aim not only to bring buildings from the lowest to the highest rating, but also to improve the mid-range by setting minimum intermediate targets (D-label).

5 Energy Savings Deficit in retrofitted buildings

5.1 Introduction

This section studies the correlations between the expected and achieved savings obtained through building retrofit, similar to the analysis by Khoury (2014), but on a larger scale. The analysis of consumption values in renovated buildings is performed on a sub-sample of the CECB dataset (the same use in Section 4) and it will provide new insight whether and, if so, which types of buildings realise their reduction potential by energy retrofit (as a function of the depth of retrofit).

The over-consumption of a building after retrofit it is often called Rebound Effect, according to which, after a building retrofit, only a portion of the expected energy savings are achieved in practice due to changes in occupant behaviour (Druckman et al., 2011). Mathematically, Galvin (2014) defined the rebound effect as a proportionate change in energy services consumption as a percentage of the proportionate change in energy efficiency. However, this explanation, adopted from the economic domain, implies that improvements in energy efficiency make energy services cheaper or more convenient, and therefore encourage increased consumption of those services (Sorrell et al., 2009), it can be misleading and confusing as thermal retrofits produce very large increases in energy efficiency, while this relationship is meaningful only for very small changes in efficiency.

Moreover, the trend of the EPG identified in this work shows that normally a building before renovation (labels E, F, G) consumes less than expected (prebound effect), while after renovation it moves in a better energy class (labels B, C) and consumes more than expected (rebound effect). The observed EPG between theoretical and actual consumption (independent of energy retrofit) could explain part of this rebound effect.

However, it remains crucial to better understand how much energy can actually be saved from energy efficiency measures. In order to do this, a different formulation was found in literature, the Energy Savings Deficit (ESD), that is generally defined as the shortfall in savings, after an energy retrofit, as a proportion of the expected savings (Druckman et al., 2011; Galvin, 2014; Haas and Biermayr, 2000):

$$ESD\ [\%] = \frac{Calculated\ savings\ -\ Actual\ savings}{Calculated\ savings}$$

Equation 2

The ESD gives a direct and simple measure of how well an energy saving target has been achieved. It is useful for engineering assessments of retrofits, for energy planning, and as a first indication of possible problems related to functioning of the equipment and/or to user behaviour.

5.2 Theory

5.2.1 Energy savings

In this study the energy consumption of a building is referred to in two fundamentally different ways: as theoretical energy use (the one predicted following the national standard) and as actual energy use (the effective consumption derived by energy bills). Therefore, when analysing a building that has undergone an energy retrofit, it is necessary to consider four different energy values, i.e. theoretical and actual as well as before and after retrofit (in this work "before" and "after" are always used depending on the time of the energy retrofit).

Consequently, the two terms of the Equation 2, "Calculated savings" and "Actual savings" can be defined using these four different values, resulting in different definitions for the savings and for the ESD. As a result, the calculated savings can be expressed as:

$$Theoretical\ savings\ \left[\frac{kWh}{m^2}\right] = Theoretical\ consumption\ before - Theoretical\ consumption\ after$$

Equation 3

Equation 3 represents exclusively the difference between theoretical values, independently from the actual consumption of the building.

$$Anticipated\ savings\ \left[\frac{kWh}{m^2}\right] = Actual\ consumption\ before - Theoretical\ consumption\ after$$

Equation 4

Equation 4 instead considers the actual consumption of a building before renovation as the starting point on which calculate the energy savings.

Both this savings, Theoretical and Anticipated, fall within the definition of "calculated savings", as both rely at least partly on calculations related to the consumption of the building after retrofit.

On the other hand, the actual consumption of a building before as well as after the energy retrofit in order to calculate the Actual savings, as shown in Equation 5.

$$Actual\ savings\ \left[\frac{kWh}{m^2}\right] = Actual\ consumption\ before - Actual\ consumption\ after$$

Equation 5

In all the presented Equations (3, 4, and 5) consumption is always intended as final energy consumption for thermal use (space heating + domestic hot water). A summary of all the presented values is reported in Figure 27.

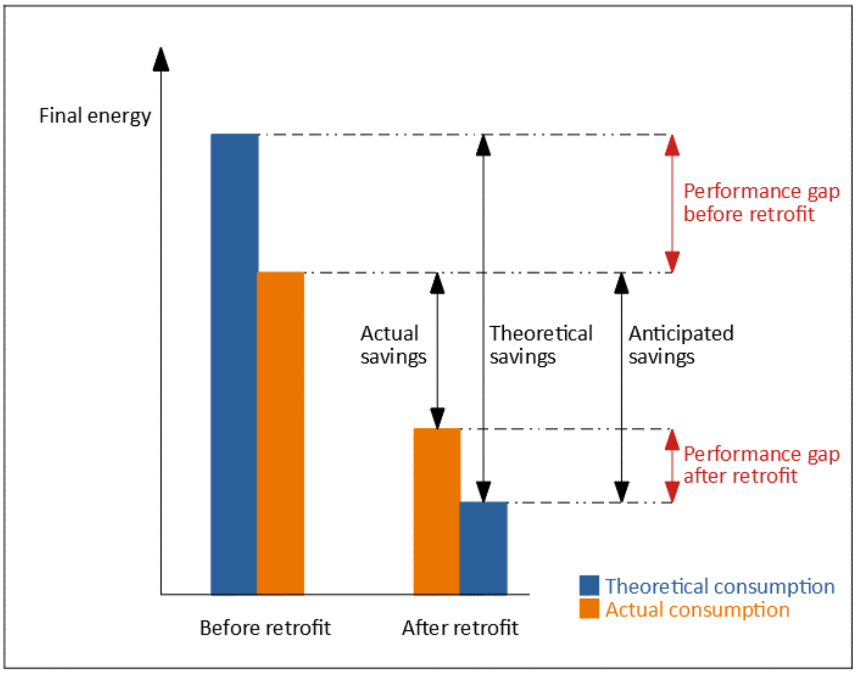


Figure 27: Differences between theoretical and actual energy consumption, before and after energy retrofit.

The identified savings are finally used to calculate two variants of the ESD (Equation 2):

The Energy Savings Deficit Regulatory (ESDr), using as Theoretical savings as the calculated one.

$$ESDr\ [\%] = \frac{Theoretical\ savings\ -\ Actual\ savings}{Theoretical\ savings}$$

Equation 6

The Energy Savings Deficit Anticipated (ESDa), using the Anticipated savings as the calculated one.

$$ESDa\ [\%] = \frac{Anticipated\ savings\ -\ Actual\ savings}{Anticipated\ savings}$$

Equation 7

The ESDr can be a useful indicator for policy makers, as it gives a clear understanding of how far the theoretical savings are from the real ones. An example is the energy retrofit that leads to an increase of the rating of the energy certificate of a building. In this case the theoretical savings are calculated in function of the number of labels gained through retrofit, and they can be used to set the targets for national or cantonal renovation strategies. For the sake of clarity, the terms Label improvement is used in this work defined as the difference between the energy labels gained through renovation (e.g. before retrofit energy label equal to D, after retrofit energy label equal to B, Label improvement equal to 2).

The ESDa can be a useful indicator for the building owner, that being in possession of actual energy consumption data before retrofit, can use this information to estimate the energy savings it will obtain from a certain retrofit, and consequently assess the costs of the operation.

5.3 Data

A subsample of the CECB dataset was produced which consists of residential buildings that have a CECB certification both before and after renovation and included real (billed) energy consumption for both. At first, only the buildings with a multiple CECB version were selected, creating a starting sample of 14 076 CECB. Thereafter, all the buildings for which the actual consumption was missing were deleted, reducing the sample to 10 178 CECB. At this point all the multiple version of CECB for the same building were deleted, keeping only the certificates in which the energy label was changing, which means that the building has been retrofitted between one certificate and the other. This operation reduced the sample to 4554 certificates, equal to 2277 buildings with two certificates each, before and after energy retrofit.

Analysing the single buildings, it was found as the CECB released after retrofit was often reporting the same actual consumption declared in the CECB before, which means that new data on actual consumption were not recorded yet. Therefore, all these cases were deleted reducing the sample to 1756 buildings. Moreover, it was found that some buildings were downgraded in energy ranking when retrofitting (for not identified reason). Being beyond the scope of this research they were deleted from the sample (in spite of deserving further analysis). As a consequence, the sample further decreased to 1575 buildings. Finally, the outliers in the energy consumption were removed. Outliers in this case are buildings with energy consumption values which are extremely different from other buildings and which were hence considered to be highly atypical buildings or possibly erroneous data. To identify them, the modified Z-scores method was used as proposed by Iglewicz and Hoaglin (1993) with a score threshold of 3.5 as suggest by the authors. This last filtering operation reduced the sample to the final size of 1172 residential buildings with a certification before and after retrofit.

Figure 28 shows the distribution of the number of buildings and the corresponding total energy reference area as function of the energy labels in the sample before (in blue) and after (in orange) the energy retrofits. It must be stressed that this sample, being a relatively small subsample of the CECB dataset, is not likely to be representative of the building stock as a whole. However, it constitutes a useful and important case study on the characteristics of retrofitted buildings.

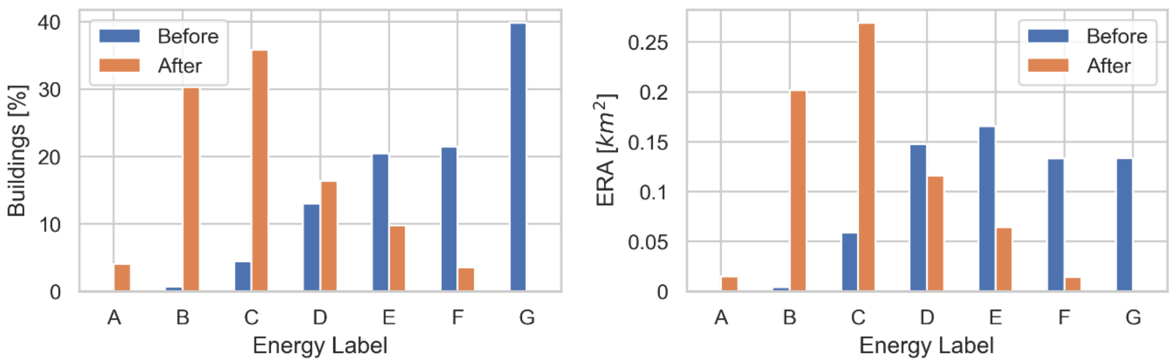


Figure 28: Distribution of energy labels before and after retrofit for the selected sample.

Figure 28 shows clearly that most buildings are in a rating lower than D before retrofit to move to a higher than D afterwards. Moreover in the sample after retrofit the distributions are similar for the number of buildings and ERA, while in the sample before there is a notable exception of G, for which there are more buildings relative to the ERA, indicating that these label categories are primarily found among smaller residences.

5.4 Results

5.4.1 Main energy figures

The first analyses focus on the characterization of the sample used. Figure 29 presents the entire building sample, before and after retrofit, showing that before retrofit the large majority of buildings have a label equivalent to or lower than D-label, while after retrofit become equivalent or higher than D-label.

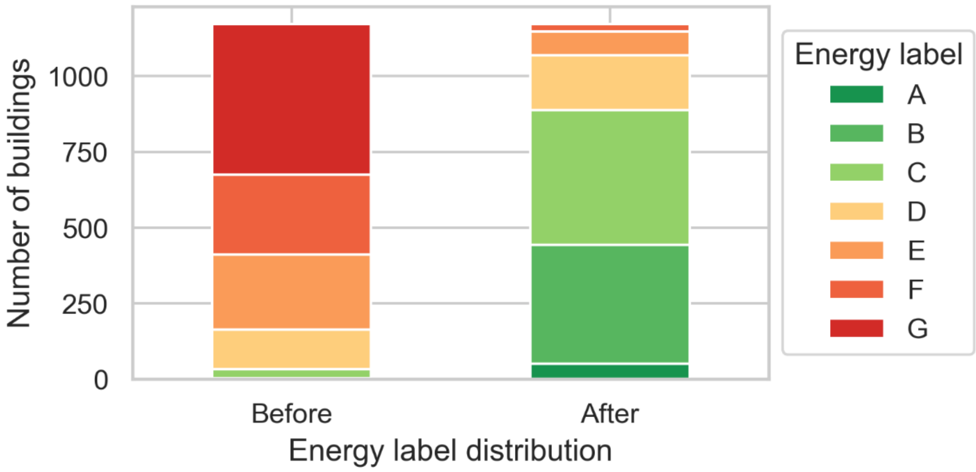


Figure 29: Energy label distribution before and after retrofit.

Figure 30 shows the depth of the energy retrofit expressed through the energy label gained after the retrofit (Label improvement) and the energy label reached (e.g. Label improvement: 4 and Label after: C, therefore Label before: G).

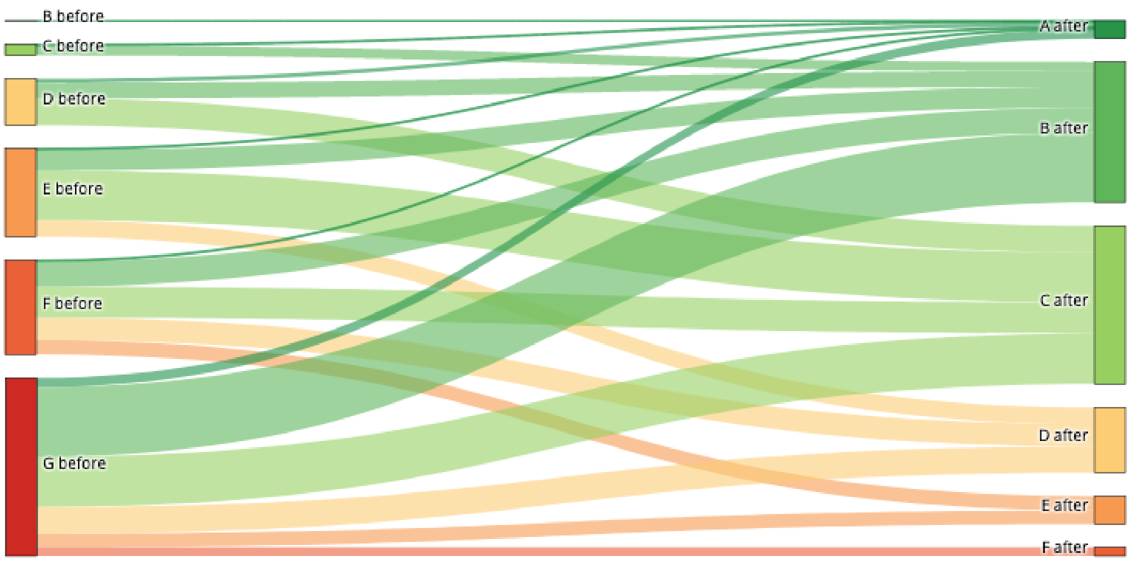


Figure 30: Depth of the energy retrofit expressed through the gained energy labels (Label before and after retrofit).

As expected, all the buildings with Label improvement equal to 5 and 6 are reaching the labels A and B, since they are the only possible targets for such deep retrofits. After a low-impact retrofit (Label improvement 1) the energy label achieved is quite heterogeneous (C, D, and E), showing that minor improvements operations (e.g. replacing of the windows or of the heating system) are executed regardless of the initial stage of the building. The sample size for each label improvement, together with the energy label after retrofit are reported in Table 10.

Table 10: Sample size and breakdwon for different label improvement.

Label improvement	Total buildings	Energy label after retrofit	Buildings	Buildings %
1	214	A	2	0.9
		B	27	12.6
		C	75	35.0
		D	46	21.5
		E	40	18.7
		F	24	11.2
2	288	A	4	1.4
		B	44	15.3
		C	139	48.3
		D	63	21.9
		E	38	13.2
3	230	A	11	4.8
		B	58	25.2
		C	87	37.8
		D	74	32.2
4	216	A	4	1.9
		B	70	32.4
		C	142	65.7
5	198	A	4	2.0
		B	194	98.0
6	26	A	26	100.0

As it is shown in Table 10, the cases with a Label improvement 3 and 2 present a majority of buildings retrofitted up to C-label. This result is interesting because it shows what is considered to be a good compromise between the depth of renovation and the expected energy savings. In the case of Label improvement equal to 2, 50% of the buildings are achieving the C-label, highlighting that medium impact energy retrofit is undertaken mainly for building with medium-low rating (E label).

A summary of the main energy and emission characteristics for the sample used in this work is reported in Table 11.

Table 11: Main figures of the CECB sub-sample.

	Before	After
Total Theoretical consumption [GWh/y]	101	39.9
Total Actual consumption [GWh/y]	79.4	41.7
Total Theoretical CO_2 emissions [$ktCO_{2-eq}$/y]	25.3	8.62
Total Actual CO_2 emissions [$ktCO_{2-eq}$/y]	20.1	9.25
Total ERA [km^2]	0.54	0.58
EPG [%]	-22.9	2.11

From Table 11 it can be noticed that the theoretical energy savings would be 60%, while the actual savings are limited to 47%. However, independently of how the savings are calculated, due to the energy retrofit a global halving of the (actual) energy used and (actual) CO_2 emissions for thermal purposes has been achieved, despite an increase of the 7% in the ERA.

Table 12 reports the values of energy consumption per building and per square meter, all presented as final energy to highlight the great improvement achieved at the level of individual building. The median value of actual consumption per square meter before energy retrofit according to the CECB subsample equals 147 kWh/m^2y (Table 12) which is practically identical to the total national average for SH (with climate correction) and DHW according to the Odyssee database (144 kWh/m^2y) (Odyssee Project, 2018).

Table 12: Final energy consumptions of the CECB sub-sample.

	Median Before	Median After
Theoretical consumption per building [MWh/y]	55.4	15.9
Actual consumption per building [MWh/y]	37.2	18.0
Theoretical consumption per square meter [kWh/(m^2y)]	200	53.2
Actual consumption per square meter [kWh/(m^2y)]	147	59.3

Figure 31 shows how the energy consumption distribution changed after retrofit, with an overall reduction and adjustment of the actual values to those theoretical, leading to a reduction of the EPG in the sample.

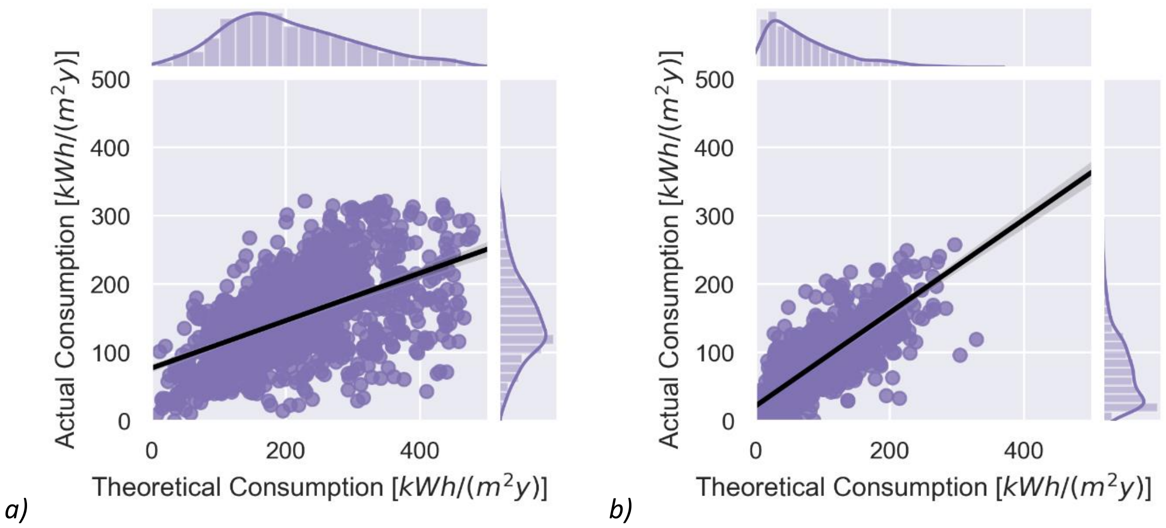


Figure 31: Relation between theoretical and actual final energy consumption a) Before and b) After retrofit (each dot represents the theoretical and actual consumption for a building).

For the renovated buildings there is no substantial difference in the EPG, i.e. the actual consumption is very similar to the theoretical consumption, as can be seen in the comparison in Figure 32. This means that for the same energy label there seems to be no difference between before and after renovation (i.e. the median EPG for D-label before renovation is equal to -5.8% and after is equal to -4.1%, so no main differences due to the retrofit are highlighted).

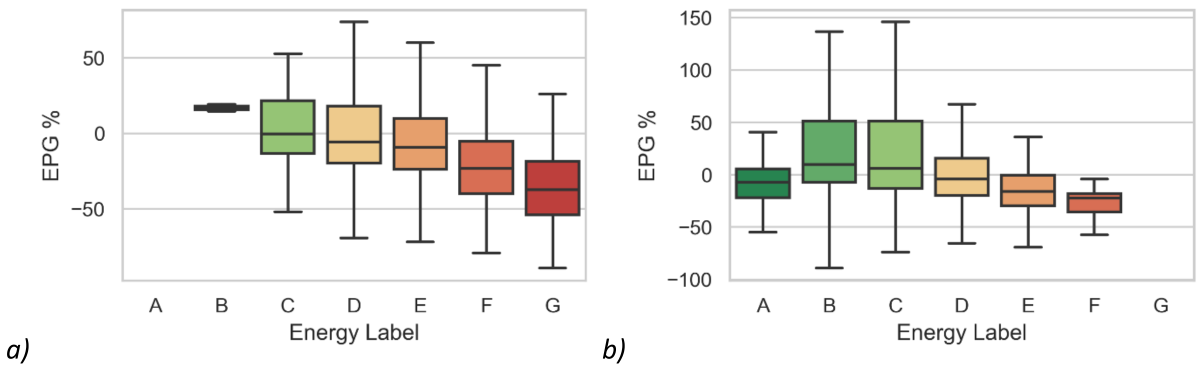


Figure 32: Energy Performance Gap a) Before and b) After retrofit.

Similar conclusions can be drawn for the final energy consumption per meter square per energy label. Table 13 shows that the energy consumption of the same energy label after retrofit is very close to the equivalent one of the entire CECB sample, representative of the building stock. However, it is important to notice that high performance building after renovation seems to perform better than the equivalent not renovated, notably -42% in actual energy consumption for A labels (23.3 vs 40.0 kWh/(m^{2}y), and -47% for B labels (and -18% for C label). We have no basis to check whether this reflects reality or whether the extensive data cleaning explained in section 5.3 may have eliminated datasets which should actually have been included (e.g. removal of buildings that were downgraded in energy ranking; rigorous removal of outliers). This seems possible if one considers the very significant improvement in energy efficiency from 147 kWh/(m^{2}y) to 59 kWh/(m^{2}y) due to energy retrofit (Table 12), which may not represent country average.

Table 13: Final energy consumption per energy label, before and after retrofit and for the building stock.

	Median Theoretical Consumption [kWh/m²y]			Median Actual Consumption [kWh/m²y]			Median EPG [%]		
Energy label	CECB Sample	Before	After	CECB Sample	Before	After	CECB Sample	Before	After
A	39.4	-	25.5	37.1	-	23.3	-6.19	-	-7.21
B	41.9	39.3	24.5	50.2	45.4	26.5	12.5	16.8	9.86
C	78.9	55.1	56.0	84.5	66.4	69.5	3.57	-0.29	5.95
D	121	119	110	116	115	103	-5.22	-5.83	-4.08
E	164	153	150	138	144	120	-15.4	-9.21	-16.2
F	202	202	191	151	150	145	-24.3	-23.4	-22.4
G	308	288	-	174	174	-	-40.4	-37.3	-

The analysis on the heating system (Figure 33) revealed that in most of the cases the type of heating system used before and after retrofit is identical (Electric heating, Gas and Wood system), with a notable difference for the oil systems. Approximately half of the oil-fired heating systems used before retrofit were replaced by heat pumps, contributing to the decarbonization of the heating supply.

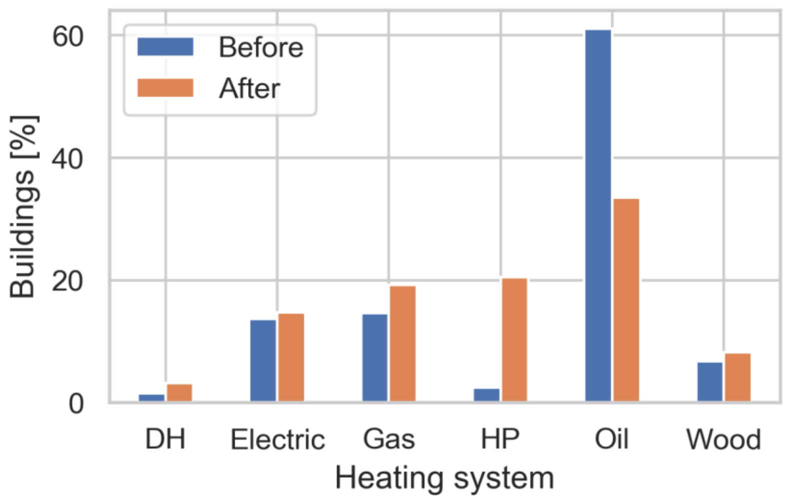


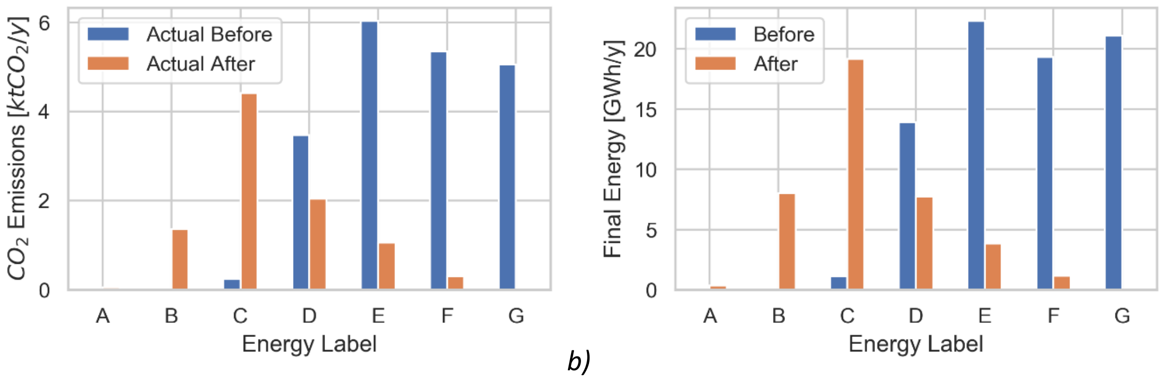
Figure 33: Heating system used in the building sample before and after retrofit.

However, when comparing the carbon content of the heat supply per energy label (Table 14), resulting from the different heating systems used in each label, no significant difference is found. This means that buildings with a certain energy rating generally use the same heating system, regardless of whether they are retrofitted or not. It also implies that the increase of heat pumps according to Figure 32 is primarily related to buildings which are renovated to A and B labels (according to Table 14, CO_2 emissions below 0.2 kg CO_2 per kWh are only found for energy labels A and B).

Table 14: Actual CO_2 emissions before and after retrofit and for the CECB sample.

	Actual CO_2 Emissions [kg $CO_{2\text{-eq}}$/kWh]		
Energy label	**Before**	**After**	**CECB sample**
A	-	0.109	0.108
B	0.102	0.122	0.129
C	0.205	0.199	0.202
D	0.243	0.246	0.250
E	0.251	0.254	0.251
F	0.263	0.222	0.238
G	0.222	-	0.215

Figure 34 shows a very similar pattern for CO_2 emissions (a) and final energy (b) before retrofit and likewise after retrofit. This reflects once more that the carbon content remains practically unchanged within the different energy labels. At the same time, the shift of buildings across labels does enable major CO_2 abatement, namely by approximately 10 kt CO_2 in this sample (difference between the total of all blue and all orange bars in Figure 34a).



a) b)

Figure 34: CO_2 emissions (a) and final energy (b) per energy label before (in blue) and after (in orange).

Finally, it should be noted that the total CECB dataset and the sub-sample before renovation are very similar, in terms of energy consumptions, CO_2 emissions and EPG (compare Table 13 and Table 14), which could suggest a prevalence of unrenovated buildings in the CECB dataset.

5.4.2 Energy Savings Deficit

Further calculations have been performed to explore the difference between theoretical (difference between the two theoretical energy consumptions), anticipated (difference between current real energy consumption and expected energy consumption of the renovated building) and actual (difference between the measured energy consumption before and after renovation) savings.

The clearest relationships were found when considering only the depth of the renovation (Label improvement), rather than the energy label either before or after retrofit, as presented in Figure 35.

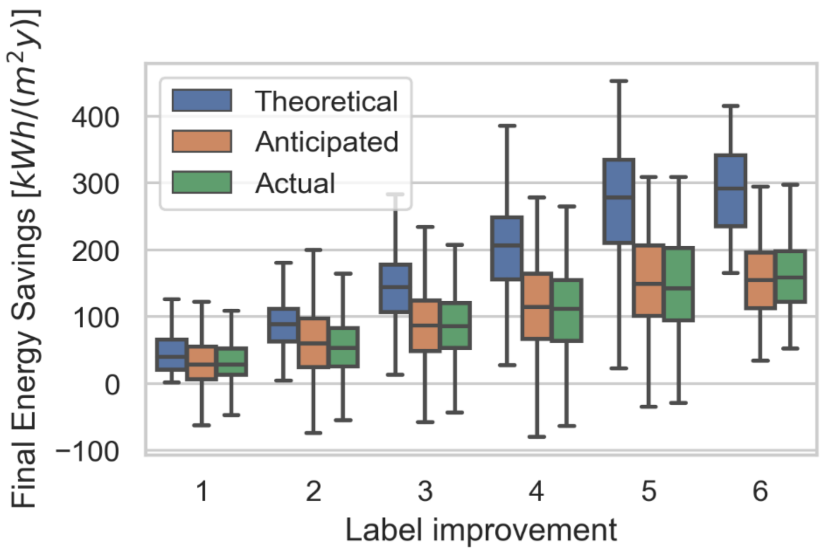
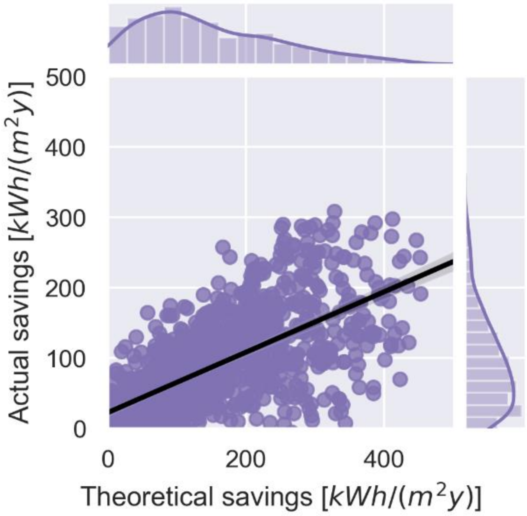


Figure 35: Distributions of energy savings according to the different calculation methods.

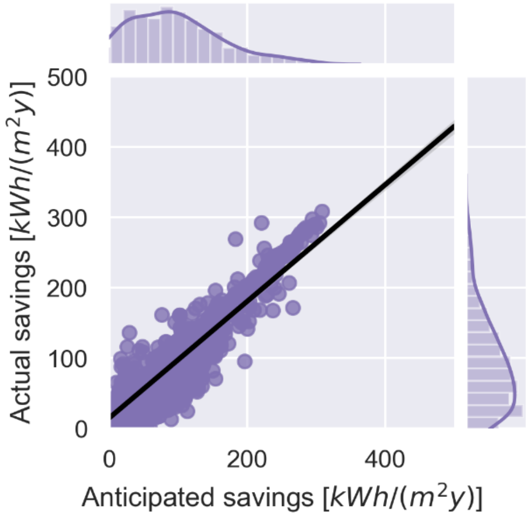
Figure 35 shows that the energy savings in absolute values, expressed in kWh/(m^{2}y), are increasing with the depth of the renovation. It is interesting to note that the theoretical savings grow steadily (as expected) as the Label improvement increases, and much more strongly than the actual savings. Actual savings are up to around half of the theoretical ones for label improvements 3 to 6. On the contrary, anticipated and actual values are always very close, implying that anticipated savings predict rather well the actual savings.

The boxplot in Figure 35 shows that no single theoretical value is negative, which means that the retrofits (at least in the sub-sample that has been used) always aimed to save energy. Nevertheless, actual savings show some negative values, indicating that some buildings consume more final energy per meter square after retrofit.

The fact that anticipated savings are a good proxy for actual savings is even more evident when comparing the distribution of values within the sub-sample (Figure 36). As shown in Figure 35, the theoretical savings deviate much more from the actual savings (Figure 36a) than the anticipated savings do (Figure 36b).



a)



b)

Figure 36: a) Actual vs. Theoretical savings and b) Actual vs. Anticipated savings.

All the three types of savings are used to calculate the Energy Savings Deficit regulatory (ESDr, Eq. 7) and the Energy Savings Deficit anticipated (ESDa, Eq. 8) as a function of the Label improvement. Both the indexes reported in Table 15 represent the shortfall in energy savings with increasing depth of retrofit.

Table 15: Energy Savings Deficit.

Label improvement	ESDr [%]	ESDa [%]
1	15.6	17.2
2	35.4	9.50
3	35.7	3.26
4	39.4	2.73
5	45.6	1.98
6	42.6	-1.91
Median	***37.3***	***3.6***

The last row of Table 15 shows the median values within the whole sub-sample, meaning that based on the theoretical values (ESDr), only 62.7% (100% – 37.3%) of the savings are actually achieved. Instead when using the anticipated values, 96.4% (100% - 3.60%) of the savings are actually achieved (ESDa). It can once more be concluded that ESDa is a very good predictor for the real savings, with the exception of buildings which improve their label by only one to two steps. To better understand the results in Table 15, the corresponding energy savings deficits and achieved energy savings are reported in Figure 37 and Figure 38. In these figures the calculated savings in Eq.2 are set equal to 100%. The bar sections ESDr and ESDa (in orange) represent the shares of the achieved savings (in blue).

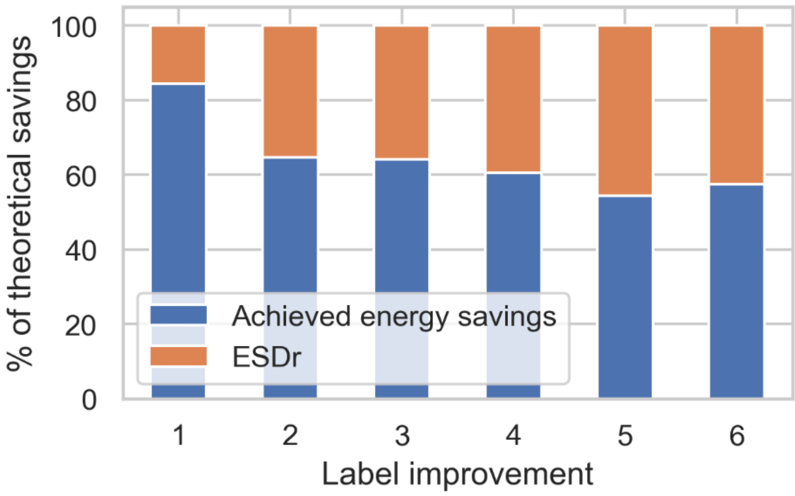


Figure 37: Fraction of achieved theoretical savings as a function of the number of energy label improvement steps (Label improvement).

Figure 37 shows that the ESDr increases with the label improvement, and the energy savings obtained through a deep retrofit (Label improvement 5 and 6) are only about half of the theoretical values. This result, together with the findings on the EPG, suggest that the ESDr it not a useful indicator to evaluate the success of an energy retrofit, as most of the shortfall in energy is due to an over-estimation of the consumption of the building before the retrofit. Therefore, the ESDr it not appraising the quality of the retrofit itself, as is it biased due to the erroneous calculation of the maximum (theoretical) achievable savings.

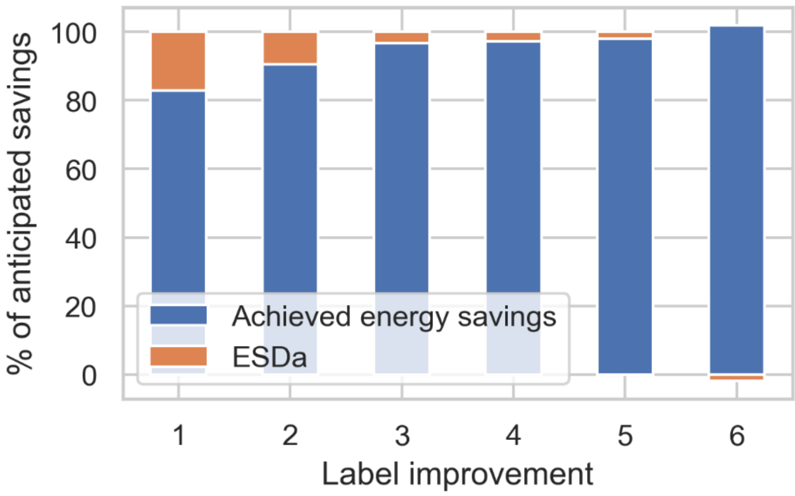


Figure 38: Fraction of achieved anticipated savings as a function of the number of energy label improvement steps (Label improvement).

Figure 38 shows an opposite trend opposite to that observed by the ESDr. The ESDa decreases with higher levels of Label improvement (it becomes even slightly negative for label improvement 6 which means that somewhat more energy was saved than anticipated). These findings suggest that the overall quality of the energy retrofitting performed within this sub-sample is very high, as the anticipated savings are fully achieved. The ESDa proves to be an excellent indicator for judging the success of a retrofit, as any failures of the newly installed systems or improper operation by users would be directly reflected by a higher ESDa.

Finally, the same type of analysis is repeated for CO_2 emissions. Figure 39 shows the CO_2 savings according to the three calculation methods, highlighting a trend very similar to the one of Figure 35 for the energy savings.

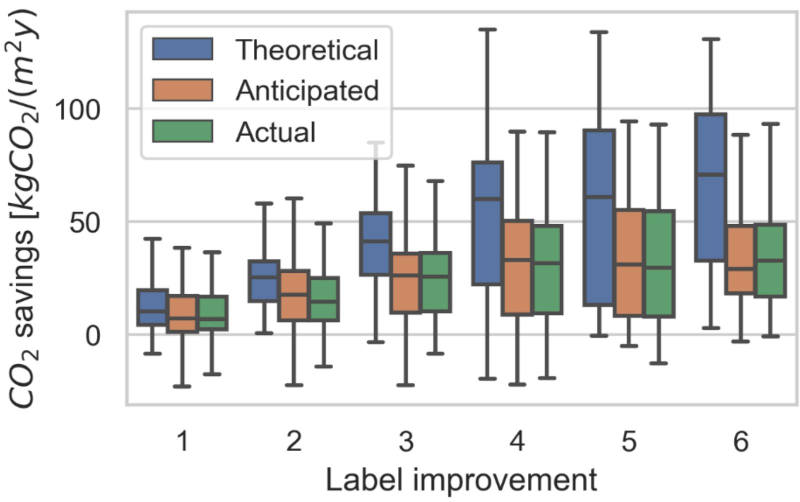


Figure 39: Distributions of CO_2-eq savings according to the different calculation methods.

It is important to highlight the magnitude of the theoretical CO_2 savings in Figure 39, showing that for deep retrofit (label improvement 4, 5, and 6) the CO_2 savings can be very different. The comparison with Figure 35 points out that CO_2 savings do not always go along with energy savings. However, also for the CO_2 emissions it is clear that the anticipated savings are more representative of the actual than the theoretical ones.

5.5 Conclusions

In this section we investigated the correlation between the expected and achieved savings obtained through energy retrofit. Three definitions of energy savings before/after retrofit were used: theoretical (difference between the two theoretical energy consumptions before and after retrofit), anticipated (difference between current real energy consumption and expected energy consumption of the renovated building), and actual (difference between the measured energy consumption before and after retrofit).

These savings were then used to calculate the Energy Savings Deficit (ESD), expressed as the shortfall in actual savings, after an energy retrofit, as a proportion of the expected savings. Two versions of the ESD have been proposed in this study: the ESD regulatory (ESDr) defined using the theoretical savings as the expected ones, and the ESD anticipated (ESDa) using the anticipated savings as the expected ones.

A subsample of the CECB dataset which consisted of residential buildings that had a CECB certification both before and after renovation and included real (billed) energy consumption for both was used for the analyses. This sample included 1172 buildings representing a useful and important case study on the characteristics of retrofitted buildings.

Independently from the calculation method, it was found that despite an increase of the heated area by 7% in the course of energy retrofit, total final energy use and CO_2 emissions for thermal purposes was halved in the considered building sample. The similarity of the results for energy and CO_2 savings highlights how the energy retrofit it is not drastically affecting the carbon content of the heat supply, as the reduction in CO_2 emissions in this sample is mainly due to the reduction of the energy used.

It was also found that energy retrofit does not affect the EPG, as for the sub-sample analysed the EPG within the same energy label was the same independently of whether the building had been renovated or not (and comparable to the one found for the whole CECB dataset in Section 4). However, a significant difference was found for the energy performance of high rated buildings, which after energy retrofit perform better in terms of actual energy consumption than buildings which have been built directly to reach the same energy label. The median energy consumption of retrofitted A label buildings is 42% lower than the median energy consumption of A label buildings which have not be retrofitted (i.e. that have been newly constructed to meet A label). Similarly, the median energy consumption for retrofitted B label buildings is 47% lower than for other B label buildings. However, these finding must be used with caution due to the limited building sample analysed.

The found ESDr is large (37%), indicating that predicting net energy savings using the theoretical demand model before and after renovation will not give reliable results. This finding may be interesting for policy makers, as the expected reduction in energy use form energy retrofit could be a considerable fraction of what was planned.

Instead, estimating real energy savings using the ESDa gives a much smaller difference compared to the actual achieved savings (ESDa 3.6%). In other words, from the perspective of a building owner considering an energy retrofit, a reasonably realistic assessment of their real energy savings can be achieved by comparing their actual current consumption with the predicted energy demand defined using theoretical calculations from the assessment norms. The ESDa is therefore an indicator of the quality of the renovation and of the expected use by its inhabitants. It is therefore not only of relevance for building owners but also for policy makers.

Finally, the comparison of ESDr and ESDa shows the choice of the right indicators can avoid encountering a significant savings gap. The analysis furthermore positively reassures that the savings objectives are often achieved, a finding that also policymakers and investors might find encouraging while keeping in mind that this analysis was based on a relatively small subset of the CECB dataset.

6 Energy Performance Gap in high efficiency buildings

6.1 Introduction

The objective of this task is to study the EPG in high performance buildings. 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. The analysis in this section therefore aims to highlight best practices to achieve the desired energy objectives. In this task three data sources were used: the Swiss Solar Agency, Energo, and Minergie databases.

Besides the quantification and insights into the performance gap on a large scale, one of the objectives of GAPxPLORE was to identify the full potential of the combined use of the different data sources. The Minergie dataset contained only theoretical energy consumptions for buildings while the Swiss Solar Agency and Energo included only measured data, therefore these were combined to obtain the theoretical and actual consumptions in order to calculate the EPG.

The Swiss Solar Agency data includes measured energy consumption (electricity, natural gas and district heat) information on roughly 150 buildings. Most of these buildings have a Minergie certificate and are therefore suitable for the purposes of this investigation. Using the information on the energy carriers we established whether the consumption meets Minergie targets and the size of the EPG was calculated. The size of the EPG was then distinguished by type of label (Minergie, Minergie-P, Minergie-A etc.) and building types. We tested whether the Minergie-P buildings, with their particularly high insulation level, show significantly different performance gaps than other types of labels.

6.2 Theory

6.2.1 Energy Performance Gap

The energy performance gap was calculated exactly as for the previous sections, using Equation 1. Both the Swiss Solar Agency and Energo databases contained only actual data, obtained through the individual metering of each building, therefore no information was given for the theoretical consumption.

The theoretical consumption, used to calculate the EPG, was approximated using the target of each standard, and therefore does not change for each building, but is a fixed value below which all buildings should be. This approximation has consequences for the interpretation of this EPG. 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. This approach was chosen because the theoretical consumption data for each building were not available for either

Energo or the Swiss Solar Agency databases, so therefore this choice to use the Minergie standards was made compulsory. Moreover, it was not possible to break down energy use by application (space heating, domestic hot water etc.) and to calculate the EPG for the thermal part as done for the previous sections. For this sample, the EPG was calculated as difference between the actual total final energy use (for all applications combined) and the calculated target for final energy, both in kWh/m^{2}y.

6.2.2 Calculation of the Minergie target for fully electrified buildings

The Minergie targets were presented in the section 1.3 (Table 4). There are six different targets, one for each Minergie standard and for both new and retrofitted buildings. These targets are expressed in terms of weighted final energy (weighted with the use of the national factor (EnDK, 2016)), by weighting the different energy carriers used in the building, and subsequently adding them up. In order to ensure a common approach in this report the reported values based on weighted final energy have been recalculated in terms of total final energy without weighting, to be then able to compare it with the actual consumption (Table 16; the latter is also reported in terms of total final energy without weighting).

Table 16: Minergie targets and re-calculated targets in final energy for completely electrify buildings.

Building standard	Building condition	Target Minergie* [kWh/m^{2}y]	Target final energy** [kWh/m^{2}y]
Minergie	New	55	35.7
	Retrofitted	90	58.5
Minergie-P	New	50	32.5
	Retrofitted	80	52.0
Minergie-A	New	35	35.7
	Retrofitted	35	35.7

** Weighted final energy* *** Total final energy without weighting*

In the case of the electricity the national factor is equal to 2, meaning that the electricity used must be multiplied for 2 to give the equivalent weighted final energy. Therefore, if the building only uses electricity, to express a weighted energy target as final energy it is simply necessary to divide it by 2. For example, the final energy target for new Minergie building equipped with heat pump is calculated in this way:

$$Minergie\ target\ /\ national\ factor = 55/\ 2 = 27.5\ kWh/m^2$$

When electricity is produced in the building with PV, a self-consumption of 30% of the PV production is assumed in the Minergie standard to calculate the Minergie index (Minergie, 2018b). The national factor used for weighting of PV energy is 0, therefore this 30% does not contribute to the total energy use with respect to the Minergie target. However, when considering final energy, it is necessary to account for the part of the final consumption that will be provided by PV. We assume that the installed PV will always provide at least 30% of the total building consumption and adjust the target in final energy accordingly. For a new Minergie building equipped with PV and heat pump for the heat supply, the target in final energy is:

$$(Minergie\ target + 30\%\ of\ the\ target\ for\ selfproduction)\ /\ national\ factor$$
$$= (55\ kWh/m^2 * 1.3)\ /\ 2 = 35.7\ kWh/m^2$$

6.2.3 Calculation of the Minergie target for buildings with non-electric heating system

For buildings that did not exclusively use electricity (e.g. those with biomass boilers), it was necessary to decompose the Minergie target for each energy carrier, each weighted with its own national factor. This was notably necessary for buildings in the Energo dataset.

Values from the MoPEC (Conferenza Cantonale dei Direttori dell'Energia CDE, 2014) were used to determine the share of energy for thermal use (space heating, domestic hot water, and ventilation) and weighted with the corresponding national factor as a function of the heating system used. The share for ventilation (always provided with electricity when present) was calculated and subtracted using the SIA 380/4 (SIA, 2006). The remaining part is entirely allocated to electricity.

Therefore, for a new Minergie building equipped with gas boiler, the thermal final energy target becomes:

$$(MoPEC\ target - Ventilation)/\ national\ factor = Thermal\ Final\ energy$$
$$= (35\ kWh/m^2 - 6\ kWh/m^2)/\ 1 = 29\ kWh/m^2$$

By subtracting the MoPEC target for the thermal part from the Minergie target (which includes other energy uses), it was possible to calculate the share dedicated to electricity consumption, and define the final electricity use for purposes other than space heating and hot water, i.e. for lighting and appliances:

$$(Minergie\ target - MoPEC\ target)/\ national\ factor = Final\ energy\ used\ as\ electricty$$
$$= (55\ kWh/m^2 - 35\ kWh/m^2)/\ 2 = 10\ kWh/m^2$$

Finally, summing up all the contributions for thermal use and ventilation (= 6 kWh/2), lighting, and appliances was possible to determine the final energy target (e.g. always for new Minergie building equipped with gas boiler):

$$Final\ energy\ target = 29\ kWh/m^2 + 3\ kWh/m^2 + 10\ kWh/m^2 = 42\ kWh/m^2$$

For these targets no self-production was calculated since the buildings with non-electric heating had no PV. Table 17 shows the original Minergie targets and the re-calculated targets expressed in terms of in final energy.

Table 17: Minergie targets and re-calculated targets in final energy.

Building condition	Building standard	Heating system	Target Minergie* [kWh/m^{2}y]	Target thermal final energy** [kWh/m^{2}y]	Target final energy** [kWh/m^{2}y]
New	Minergie	Gas	55	29	42
New	Minergie	Biomass	55	58	71

** Weighted final energy* *** Total final energy without weighting*

6.3 Data

6.3.1 The Swiss Solar Agency dataset

The Swiss Solar Agency database consisted of 149 buildings, with various destinations of use, as reported in Figure 40. The Swiss Solar Agency database contains the actual final energy consumption of each building. This data it is usually provided by the building owner at the moment of the application to the Swiss Solar Prize, justified through energy bills. Furthermore, the prize giving committee must verify this data with each local energy provider. This step is necessary as all the buildings that are applying for this prize are equipped with PV systems, but most of the energy produced is injected in the Swiss grid and is therefore not included in the consumption of the building itself. The electricity providers must confirm the total amount of electricity produced by PV, the fraction that is injected in 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, given as sum of all the different needs (space heating, domestic hot water, ventilation, lighting, appliances). When a different energy carrier than electricity was used (e.g. biomass), the owner was supposed to prove the amount of fuel used through bills. Independently of the heating system used, the verified energy consumption was always given as total final energy consumed, in kWh/y.

Once that the actual consumption was determined for each case, it was necessary to define the theoretical consumption, and for this purpose the Minergie database was used. With the help of the address and information about the location, it was possible to link each building in the Swiss Solar Agency database (when Minergie labelled) with the information of its Minergie certificate and to determine which standard kind of Minergie label it had received (e.g. Minergie, Minergie-P, Minergie-A). It was thereby possible to attribute a Minergie target to each building.

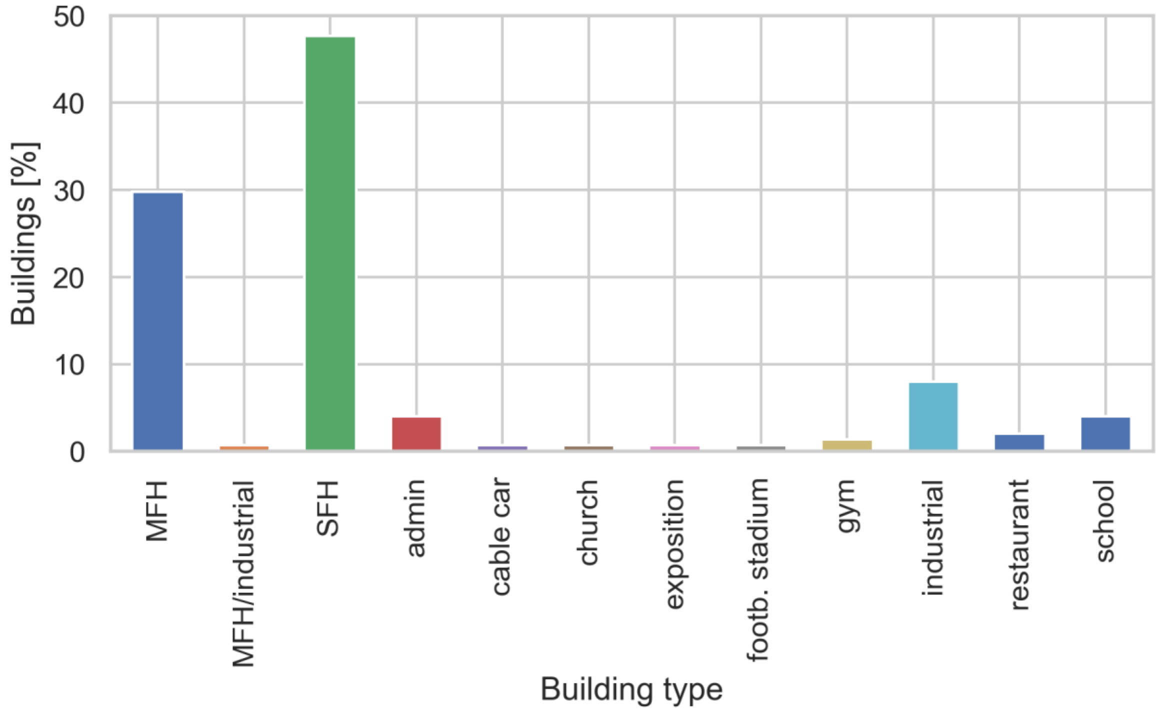


Figure 40: Building type distribution in the Swiss Solar Agency database (n = 149).

The scope of the analysis only considered the residential buildings (SFH and MFH), reducing the sample to 115 buildings. Some of these buildings were equipped with biomass or gas boiler, but it was impossible to know the share coming from the different energy carriers (i.e. the amount of gas used for the heat supply and the amount of electricity used for lighting and appliances). Therefore, only the buildings with heat pump were kept in the sample and analysed, as only in this case the information on the total final energy consumption was considered reliable, further reducing the sample 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 were kept, in order to reduce the effects due to seasonality. This last filtering operation reduced the final sample to 56 buildings. The summary of the sample used for the analysis is reported in Table 18.

Table 18: Summary of the Swiss Solar Agency sample.

Building standard	Building condition	Number of buildings
MoPEC 2014	New	5
	Retrofitted	15
Minergie	New	5
	Retrofitted	3
Minergie-P	New	14
	Retrofitted	7
Minergie-A	New	4
	Retrofitted	3

A closer look to the actual final energy distribution within the sample (Figure 41) confirms the very low consumption of the selected buildings and their high energy performance. In most buildings the final energy consumption is less than 40 kWh/m^{2}y. In Figure 42, instead, the ERA distribution across the sample is reported, showing that the ERA of most buildings is smaller than 250 m^2.

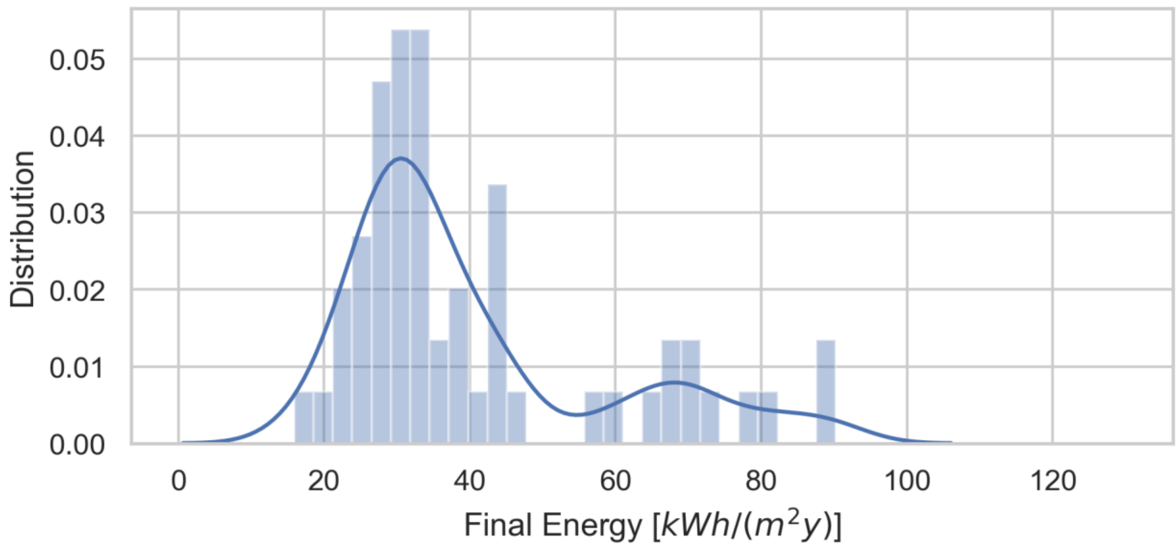


Figure 41: Final energy distribution among the buildings in the Swiss Solar Agency sample.

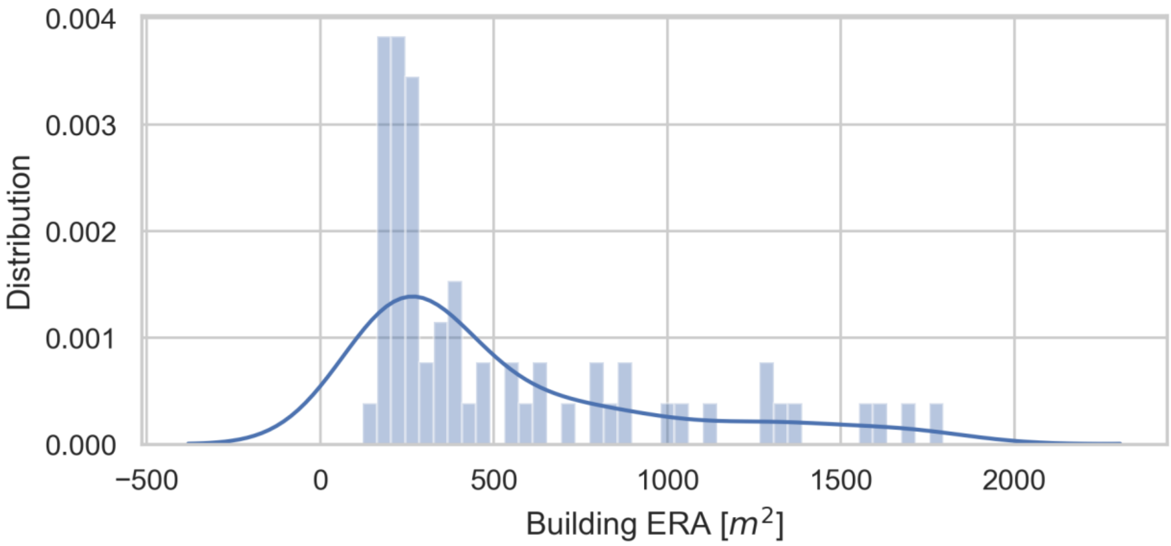


Figure 42: ERA distribution among the buildings in the Swiss Solar Agency sample.

6.3.2 Energo dataset

The Energo database contains metred data providing a total annual value of final energy consumption (without weighting) for heat (space heating and domestic hot water) and electricity (ventilation, lighting, and appliances) for each year the building is monitored. For this work, data for each building from 2014 to 2018 was averaged, giving a three-year average actual consumption similar to the CECB methodology (SIA, 2016a). Once the actual final energy consumption was obtained (as totals) it was possible to compare them to the target Minergie expressed in final energy.

The database of Energo is private and confidential, it was therefore not possible to have a full access to all information. Only the information on the Energo buildings labelled Minergie, for which therefore the design calculations were available in the Minergie database have been received. Using the building identifier codes (EGID) and addresses, each building in the Energo database (when Minergie labelled) was linked with the information of its Minergie certificate, to determine which Minergie label and energy target applied to the building (e.g. Minergie, Minergie-P, Minergie-A).

This initial sample counted 26 buildings. Many of these buildings, however, had multiple types of use (e.g. office + shop), making it impossible to break down the energy consumption as required by the analysis. Data on building with mixed use could not be exploited for our analysis because the Minergie index is calculated as weighted total based on to the different types of uses of the building, resulting in one single Minergie certificate.

In total, the 26 buildings corresponded to 42 different destinations of use, as reported in Figure 43. Since the focus of the analysis was on residential buildings, only the multi-family houses were selected for this study, reducing the sample to 8 buildings.

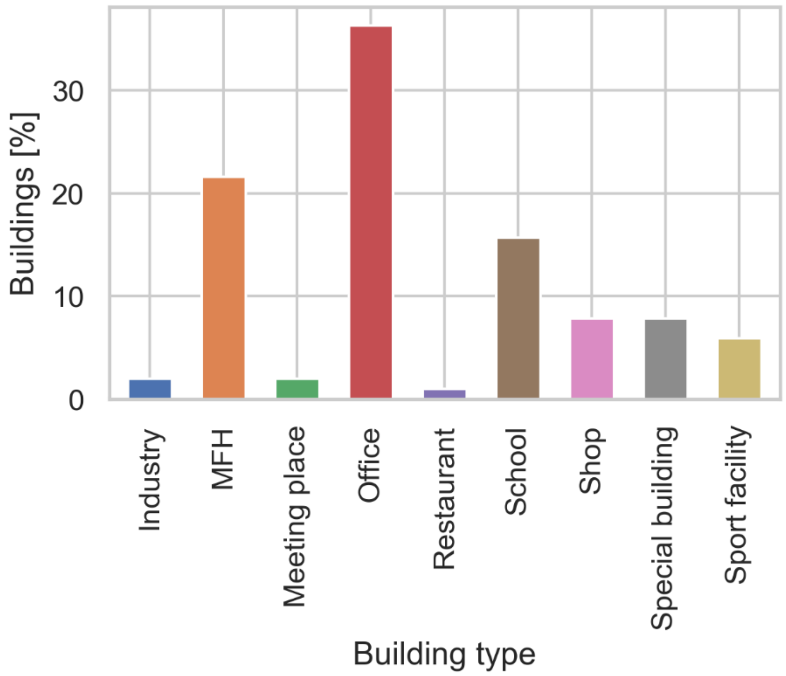


Figure 43: Destinations of use in the Energo sample.

A further selection was made based on the type of heating system used. In this case buildings with a heat pump (therefore fully electrified) were discarded due to the different ways in which Energo experts treat these types of buildings. This is because the total electricity demand according to meter readings is subdivided by the expert into the heat and electricity parts, thus affecting the quality of the initial data and making it impossible to define the actual consumption. This led to the removal of two buildings, further reducing the final sample to 6 buildings. Information on the selected buildings is given in the Table 19.

Table 19: Main figures of the Energo sample.

ID	Registration number	Type of use	Building condition	Building standard	Heating system	ERA [m²]	Built in	Ventilation system
21	VD-1432	MFH	New	Minergie	Biomass	4070	2013	Heat recovery ventilation
27	GE-817	MFH	New	Minergie	Gas	2174	2015	Heat recovery ventilation
32	VD-1317	MFH	New	Minergie	Gas	2141	2013	Heat recovery ventilation
42	GE-371	MFH	New	Minergie	Gas	3889	2013	Heat recovery ventilation
92	SO-435	MFH	New	Minergie	Biomass	1937	2013	Heat recovery ventilation
100	ZH-5746	MFH	New	Minergie	Biomass	382	2014	-

As can be seen from Table 19, all the buildings are new Minergie-labelled constructions, equipped with gas or biomass boiler. The main difference to the Swiss Solar Agency sample lies in the building size. Almost all the Energo buildings have an ERA of more than 2000 m^2, which exceeds by far the approximate average of 250 m^2 of the Swiss Solar Agency sample (Figure 42). This difference is related to the way Energo operates – it investigates only large energy consumers.

For each of the buildings analysed information was available on the actual thermal consumption (SH + DHW), but only 4 presented information on their electricity consumption. For this reason, for all 6 of them a thermal EPG analysis was carried out (as already done for the CECB sample in Section 4) and for a sub-sample of 4 of them, the EPG for total final energy was calculated.

6.4 Results

6.4.1 Swiss Solar Agency

Since the Minergie targets are different for new and retrofitted buildings, these categories are treated separately. Some buildings that respect only the MoPEC 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 20 and Table 21.

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 44.

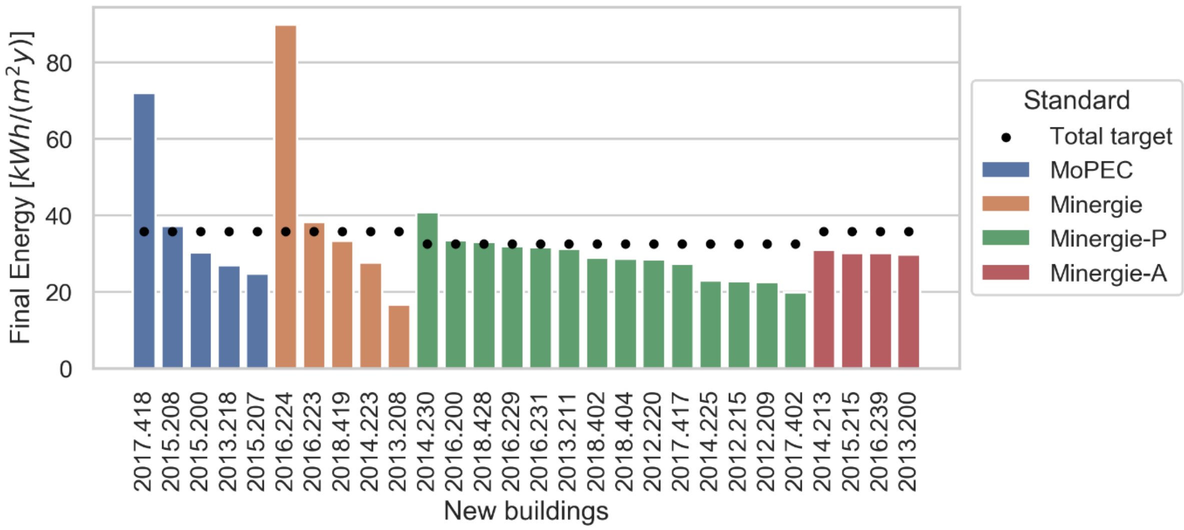


Figure 44: Actual final energy consumption per new buildings in the Solar Agency sample (n= 28).

Table 20: 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 20 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.

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 45 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 21), 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 21).

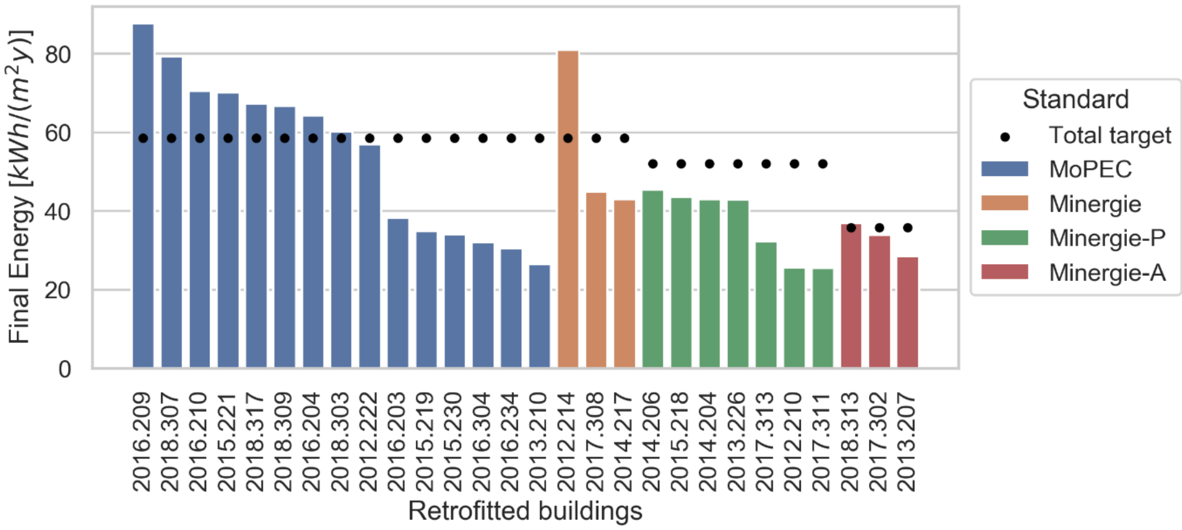


Figure 45: Actual final energy consumption per retrofitted buildings in the Solar Agency sample (n=28).

Table 21: Energy performance gap per building standard in retrofitted buildings.

Retrofit building standard	Number of buildings	Mean consumption [kWh/m^2y]	Median consumption [kWh/m^2y]	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 ($kgCO_2$-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 (Conferenza Cantonale dei Direttori dell'Energia CDE, 2014). The Minergie-P standard, despite its higher target than Minergie-A, focuses on reducing the heating demand, following the German Passivhaus model (Peper and Feist, 2015). The envelope performance must be 30% better than those prescribed by the MoPEC.

The trend in the theoretical heating demand (Qh) can be observed in Figure 46, where the residential Minergie database is analysed (more than 35 000 buildings). The theoretical heating demand is not the target value given by each standard (otherwise it would be always the same). It is calculated for each building with its effective ventilation rate (i.e. different than the 0.7 m^3/m^2h default). As shown in Figure 46, the median theoretical heating demand of the Minergie-P standard is smaller than for Minergie-A. It is also very important to note that the spread is smaller for Minergie-P (and even more so for Minergie-P-ECO) compared to Minergie and somewhat smaller than Minergie-A. The fact that the upper demand level of Minergie-P is below 30 kWh/m^2y, once more representing the comparatively low probability of an EPG.

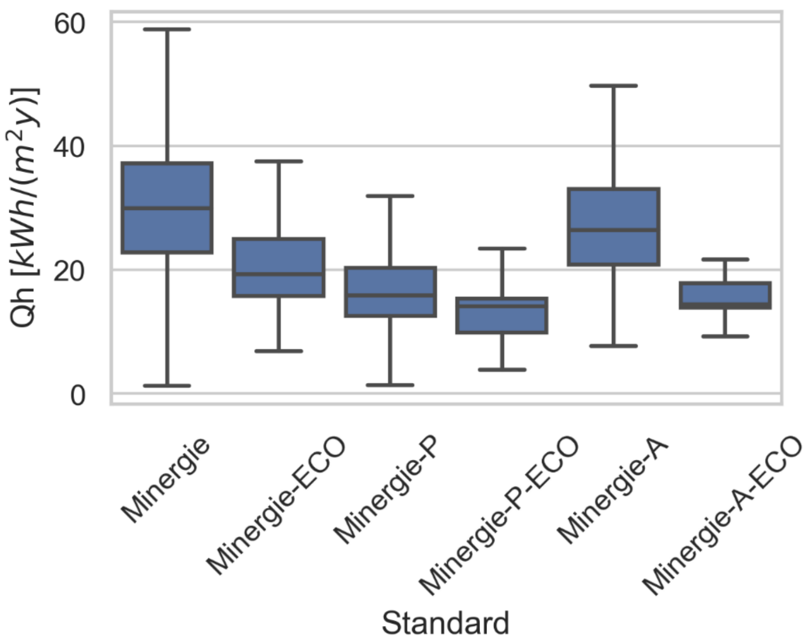


Figure 46: Theoretical heating demand (Qh) distribution in the residential Minergie database.

The Minergie index calculated for all the Minergie residential buildings is shown in Figure 47, to better understand the influence of the heating system used in the building (i.e. the energy source) compared to the envelope thermal performance, in the attribution of the Minergie index. As can be seen, the median index for the Minergie-A is negative, meaning an energy production that is greater than the building's demand. It is important to remember again that the Minergie index is calculated and expressed in weighted final energy, obtained using the national factor presented in Table 1. This explains the presence of negative values.

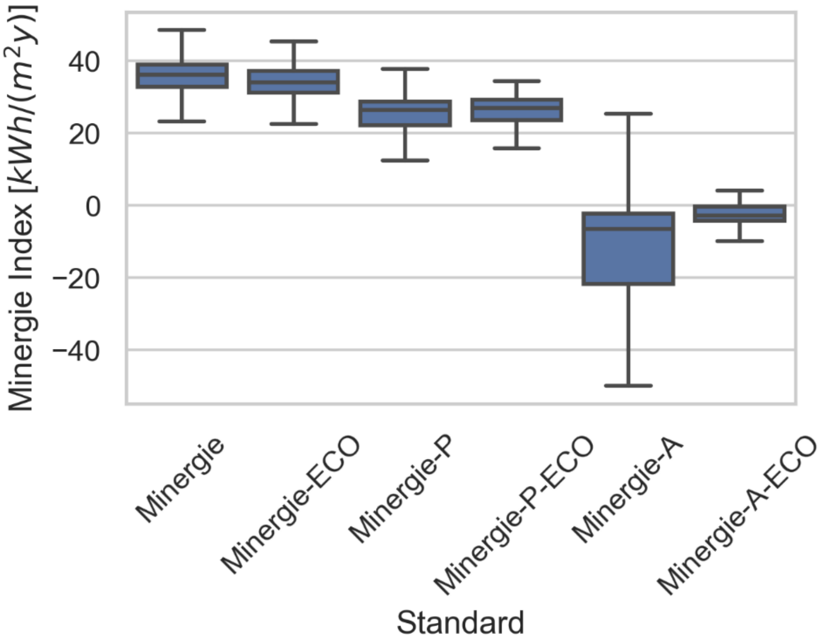


Figure 47: Minergie Index distribution in the residential Minergie database.

6.4.2 Energo

The analysis of the Energo buildings is important for comparison because the Swiss Solar Agency buildings are likely to be particularly good examples since they were submitted for an architectural prize. The Energo buildings may be more indicative of typical Minergie buildings, even if the fact that they are subject to monitoring by Energo makes them more likely to outperform the average building. The analysis on the EPG were carried out for each individual building and the results are presented in Figure 48 and Figure 49.

The theoretical consumption, used to calculate the EPG, is expressed through the Minergie target re-calculated depending on the heating systems used (see Table 17), and therefore differs among the buildings (dashed lines). In Figure 48, for each building the actual final energy consumption for thermal use (i.e. only SH and DHW), is reported. All buildings equipped with a gas-fired boiler by far overconsume compared to their objectives, leading to very high positive thermal EPGs, as reported in the column EPG thermal of Table 22.

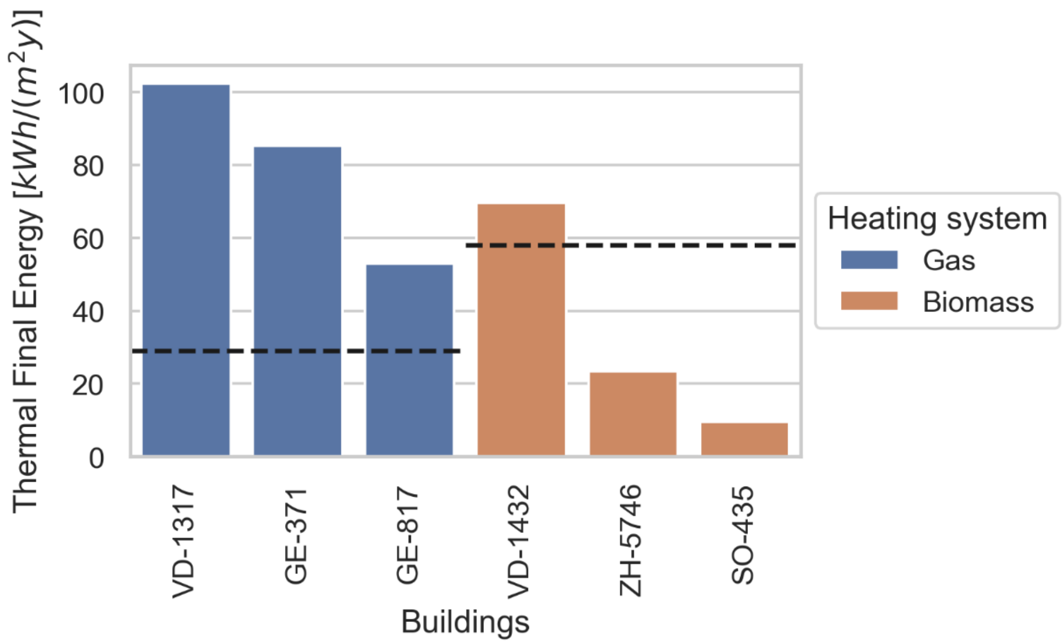


Figure 48: Actual final energy consumption per thermal use (SH+DHW) per building in the Energo sample.

Table 22: Energy performance gap per building in the Energo sample.

ID	Registration number	EPG [%]	EPG thermal [%]
32	VD-1317	351.9	252.9
21	VD-1432	105.4	20.17
100	ZH-5746	-24.62	-59.55
92	SO-435	-62.62	-83.48
42	GE-371	-	194.1
27	GE-817	-	82.64

In order to compare these results with the ones from the Swiss Solar Agency it is necessary to consider the total final energy consumption of each building, to calculate an EPG comparable to the one in Table 20 for new Minergie buildings (EPG= -6.8%). This operation was performed only for a sub-sample of buildings for which also the electricity consumption was available. As the results in Figure 49 show, the range of values on this very small sample is very high and it is therefore difficult to generalise the observations. Indeed, two buildings are consuming more than calculated and two less than calculated, leading to the large range of EPGs [%] reported in Table 22.

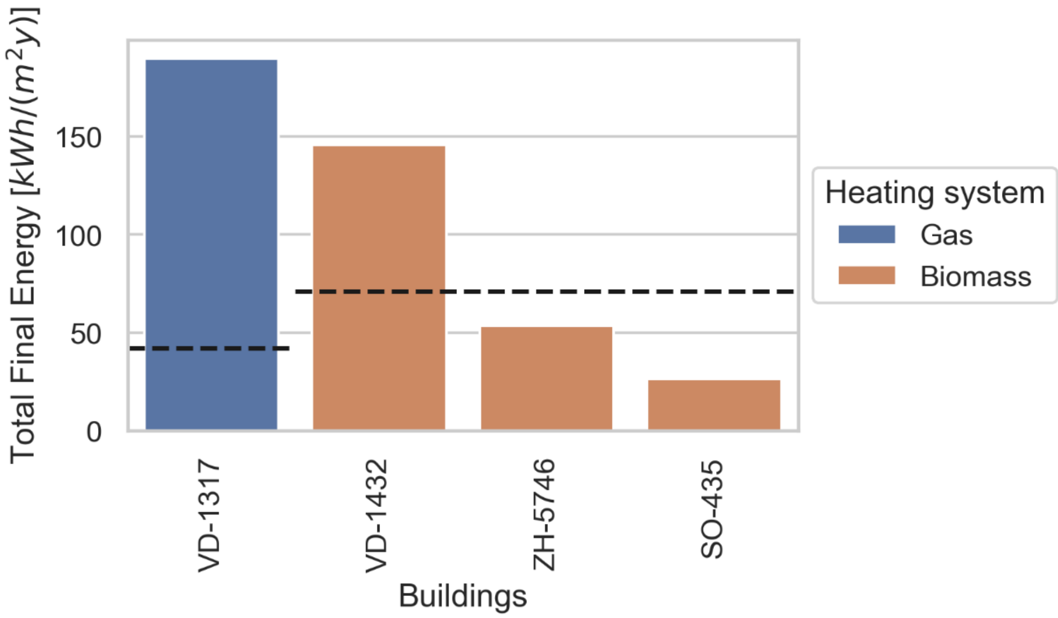


Figure 49: Actual final energy consumption per building in the Energo sample.

Nevertheless, it must be highlighted that the consumption of the two buildings consuming more than their targets (with a positive EPG respectively of 352% and 105%) are higher than those of Figure 44. The Minergie building with the highest final energy consumption in the Swiss Solar Agency sample is around 90 kWh/m^{2}y, while here one is at about 150 kWh/m^{2}y and the other at 200 kWh/m^{2}y, representing multiples of the Minergie target.

This result alone obviously cannot be generalised to all Minergie buildings (especially as two of four the buildings have a negative EPG) but underlines how a certificate alone is not a guarantee of low consumption. Instead, monitoring of the building is essential to guarantee the performance.

6.5 Conclusions

The objective of this task was to study the EPG in high performance buildings. In Switzerland, some of the most performing buildings are those certified by Minergie, therefore their database has been used for analysis. As the Minergie certificate database does not include measured actual consumption, it was linked with energy consumption data from the Swiss Solar Agency and Energo databases. The analysis focused on the different Minergie standards (Minergie, Minergie-P, and Minergie-A) to determine the relation between the label type and the EPG.

Since the theoretical consumption for each building was not available, it was necessary to use the Minergie index as the theoretical reference value. However, the Minergie indices are expressed in weighted final energy, therefore not directly comparable with the actual consumption expressed in final energy. The Minergie indexes were therefore converted to final energy demand using the various factors based on the type of use of the building, the condition (new or retrofitted), the Minergie standard obtained and the energy source used for heating. In addition, the theoretical total final energy consumption was disaggregated into components for the thermal (space heating and domestic hot water) and purely electricity (ventilation, lighting, and appliances) parts. It should be noted that the theoretical final energy consumption used in this section (derived from Minergie targets presented in Table 16 and Table 17) is conceptually not fully comparable to theoretical final energy consumption in Section 1 to 5 of this report and the respective values should therefore not be directly compared.

Once the theoretical values were calculated, the databases received from the Swiss Solar Agency and Energo were filtered and treated to reach reliable and appropriate actual consumption values. In the first case, 56 buildings equipped with PV and heat pump were obtained. In the second case 6 buildings (without PV and without heat pump) were retained.

The first finding was the very high performance of the buildings in the sample. The final actual consumption for all the energy needs of the buildings is very low, with median values of 30 kWh/(m^2y) for new buildings achieving the MoPEC standard (60 kWh/(m^2y) for retrofit), 33 kWh/(m^2y) for new Minergie buildings (45 kWh/(m^2y) for retrofit), 29 kWh/(m^2y) for new Minergie-P (43 kWh/(m^2y) for retrofit), and 30 kWh/(m^2y) for new Minergie-A (34 kWh/(m^2y) for retrofit).

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/(m^2y) for Minergie-P buildings and by 6 kWh/(m^2y) 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. The standard Minergie-A, despite having the lowest Minergie target, pays more attention to reducing the emissions per unit of energy used than reducing the demand, as the performance of the envelope is comparable to that prescribed in the standard Minergie label and in the MoPEC. The Minergie-P standard instead is fully dedicated to reducing the heating demand (useful heat). In this case the performance of the envelope must be at least 30% better than those prescribed by the MoPEC, reducing the thermal consumption of this standard to the minimum.

The results found for the Minergie buildings in the Swiss Solar Agency sample, with negative EPGs compared to their standards, are partly a consequence of the sample used. As discussed in the Data section 6.3.1, these buildings are all selected in a competition that rewards the best performance, explaining why the energy consumption of these buildings is in line with or lower than the standards. It would therefore be unlikely to find very high EPG values, representing large over-consumption. This observation motivated the analysis of the Energo buildings.

The analysis on the Energo buildings (all new construction) highlighted a wide range of EPGs, varying from -84% to 253% for the thermal EPG, and from -63% to 352% for the total EPG. In terms of actual energy consumption, two out of four buildings exceed their target, one by about 80 kWh/(m^2y) and the other by 130 kWh/(m^2y), representing multiples of the Minergie target. However, the other two buildings analysed were found below the limit, therefore in line with their expected consumption.

These findings can be considered indicative of the fact that a Minergie building can actually consume much more than anticipated, depending on how it is monitored and operated. However, the presence of Minergie buildings with extremely low consumption, even below their standards, demonstrates that it is currently possible to achieve very ambitious energy targets. Before concluding, it is important to remember that when interpreting the analysis based on the data from the Swiss Solar Agency and Minergie, a possible bias towards high energy performance needs to be considered. Inhabitants choosing to live in such high efficiency buildings may also motivated to live low-energy lifestyles. Nevertheless, the analysis offers interesting insight, e.g. on the question whether the performance gap is smaller within this sample compared to the building stock.

7 Energy Performance Gap in detailed case studies

7.1 Introduction

This section of the GAPxPLORE study is based on in-depth analysis of a limited number of buildings, carried out by analysing the calculations made during the design phase and the energy needs collected during the monitoring (Energo database). This in-depth analysis focusses on Minergie buildings. The theoretical consumption is based on calculations performed during the process of the Minergie certification. The actual consumption is collected for each building in the Energo database. The objective of the detailed analyses discussed in this section is to better understand the reasons of the performance gap. For each building the EPG has been determined considering the energy needs for heating and electricity for all applications (contrary to the first sections of this report which were limited to SH and DHW).

7.2 Dataset

As a preparative step of the analysis, it was necessary to search for Minergie buildings that were also monitored by Energo for one or more years. The Energo and Minergie database do not systematically report the EGID identifiers of buildings, so a direct and complete comparison between the two platforms was not possible. Considering that the Minergie certified buildings are new or refurbished buildings in recent years, research has focused on buildings with recent Energo contracts and in the reference area of the Energo Suisse Romande et Tessin Agency of which SUPSI is a member.

To allow a reliable analysis of the EPG, we searched for buildings with the following characteristics:

- Residential or administrative use
- Energo contract with complete monitoring, active for at least a year
- Minergie certification (any type of Minergie standard)
- Energo monitoring with complete data
- Analysis conducted by the Energo engineer with complete information on the adjustments made to the control system or recommended by the engineer
- Complete information on the building (architectural and technical systems)
- Availability of documentation and calculations produced during the MINERGIE certification phase
- Technical and architectural plans of the building

Considering the criteria listed above, the search for buildings was carried out manually instead of automatized data mining of the databases. First, 23 new buildings with an Energo contract and monitoring known to be Minergie standard were identified. Then it was checked for each building whether complete monitoring with detailed documentation was available for at least one year. Moreover, each building had to be present in the Minergie platform in a univocal way. At the end of the process, 4 buildings were identified.

7.3 Theoretical consumption

The theoretical consumption was determined for each building by examining the documentation and calculations presented during the building certification request. As discussed in section 1.3 of this report, the methods of calculating the Minergie standard include the use of weighting factors that favour or penalize various sources of energy. For this reason, the Minergie indices are not directly comparable with the expected consumption of buildings in terms of final energy. Therefore, the values extracted from the Minergie dataset were further processed to remove the weighting factors. The calculations on the energy needs in the Minergie standard were based on the SIA (Swiss society of engineers and architects) technical norms.

Norms SIA used for calculating energy needs (Minergie standard)

- Energy needs for heating SIA 380/1 (SIA, 2016b)
- Energy needs for hot water SIA 380/1
- Energy needs for cooling SIA 382/2 (SIA, 2011)
- Energy needs for ventilation SIA 380/4 (SIA, 2006) or Minergie standard values
- Energy needs for lighting SIA 380/4 or SIA 387/4 (SIA, 2017)

Other energy needs were not considered in the Minergie certification calculations. The following norms were additionally used to estimate the theoretical energy need when not available in the documentation:

- Energy needs for electrical devices SIA 2024:2015
- Energy needs for lighting SIA 2024:2015
- Energy needs for cooling SIA 2024:2015
- Energy needs for ventilation SIA 2024:2015
- Energy needs for lighting SIA 2024:2015

A variety of calculation methods are applied in the SIA standards - they can be on a monthly (for example the energy needs for heating in SIA 380/1) or on an hourly basis (for example the energy needs for cooling in SIA 382/2) or simple standard values based on the surface of the building (for example the energy needs for domestic hot water in the SIA 380/1).

When the construction of the building differs from the Minergie project (for example the building is cooled but this was not considered in the Minergie certification), the SIA 2024 norm is used to calculate the respective requirements. In the comparative analysis between the theoretical and the actual consumption we will report for each buildings the percentage of energy consumption that was not included in the design phase and has therefore been approximated in the context of this study.

7.4 Results

The results of the EPG analysis are shown below for each building.

BUILDING 1			
Year	2015		
A_e	7'536 m² (2 buildings)		
Housing	6'558 m²		
School	978 m² (Centre de vie)		
Heating			
100%	PELLETS		
Hot water			
100%	PELLETS		
PV			
4 + 5.5	kW_p		
data from Minergie			
THEORETICAL CONSUMPTION			
BUILDING SILL		**Heat**	**Electricity**
HEATING		30'528 kWh	
HOT WATER		94'774 kWh	
VENTILATION			17'738 kWh
COOLING			0 kWh
AUXILIARIES			1'800 kWh
LIGHTING			15'492 kWh
APPLIANCES			54'222 kWh

BUILDING FLCL	Heat	Electricity
HEATING	37’922 kWh	
HOT WATER	73’690 kWh	
VENTILATION		14’395 kWh
COOLING		0 kWh
AUXILIARIES		2’000 kWh
LIGHTING HOUSING		10’740 kWh
LIGHTING SCHOOL		16’626 kWh
APPLIANCES HOUSING		37’590 kWh
APPLIANCES SCHOOL		6’846 kWh
Total THEORETICAL	**236’916 kWh**	**177’449 kWh**
	31.43 kWh/m^2	23.55 kWh/m^2
ACTUAL CONSUMPTION		
BUILDING SILL + FLCL	**Heat**[3]	**Electricity**
2015	435’156 kWh	180’113 kWh
2016	480’685 kWh	208’015 kWh
Total average ACTUAL	**457’920 kWh**	**194’064 kWh**
	60.76 kWh/m^2	25.75 kWh/m^2

[3] Is considered the heat delivered to the building, not the burnt fuel (pellets)

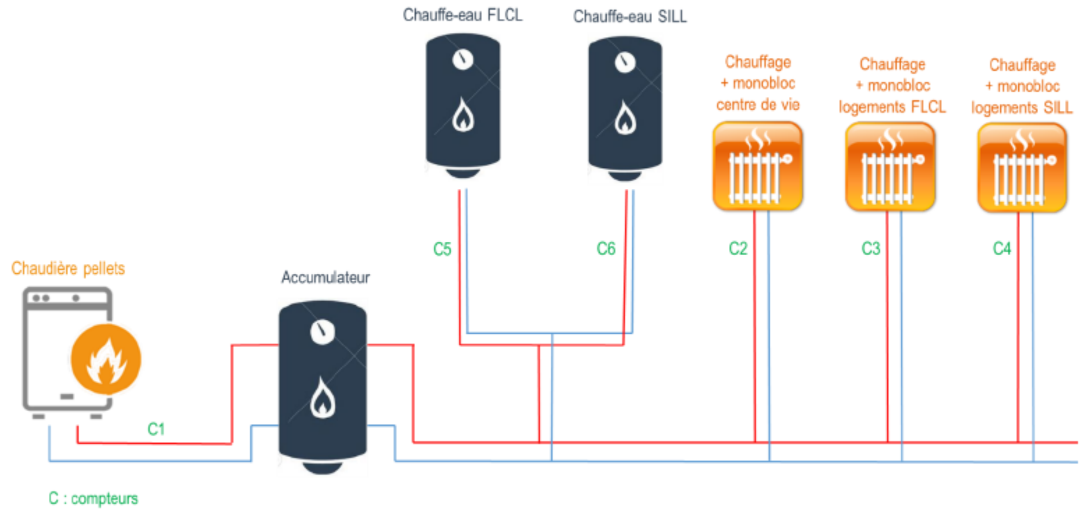
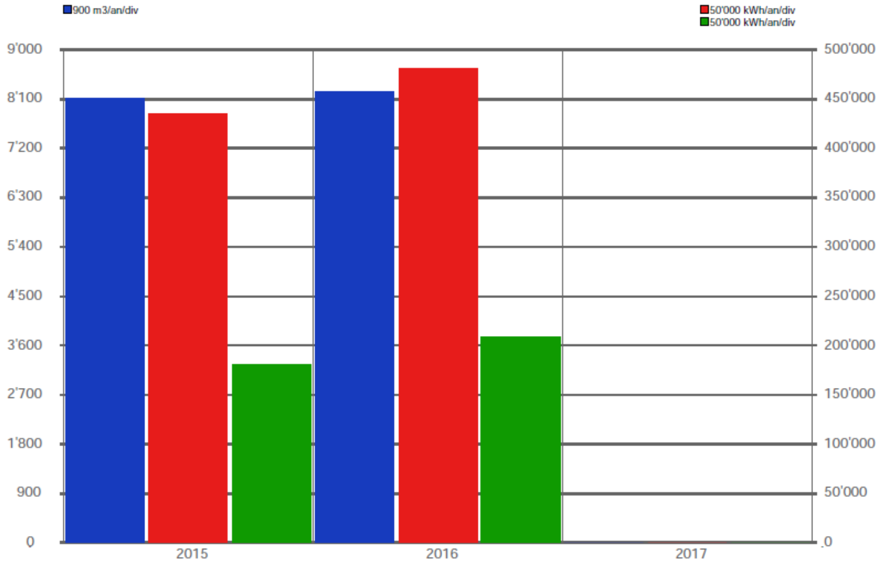


Figure 50: Position of heating meters. Source: Energo



Courbe	*Batiment - description fluide - adresse fluide*		*Date début*
1	Lausa	au cpt. général (Eau/MANU) - 12584493	01.03
2	Lausa	OTAL CHALEUR primaire (Chaleur/MANU) - Chauffage+ECS	01.03
3	Lausa	L EL (hors PV) (Electricité/VIRTUEL) - communs+locataires(logo+MC)	01.03

Courbe	1	2	3
Unité	m3	kWh	kWh
2015	8'102	435'156	180'113
2016	8'219	480'685	208'015
2017			

Figure 51: Annual evolution of energy consumption (Water, Heat, Electricity). Source: Energo

ENERGY PERFORMANCE GAP		
	Heat	***Electricity***
Total THEORETICAL	**236’916 kWh**	**177’449 kWh**
	31.43 kWh/m^2	23.55 kWh/m^2
Total average ACTUAL	**457’920 kWh**	**194’064 kWh**
	60.76 kWh/m^2	25.75 kWh/m^2
EPG	**+ 93.28 %**	**+9.36 %**

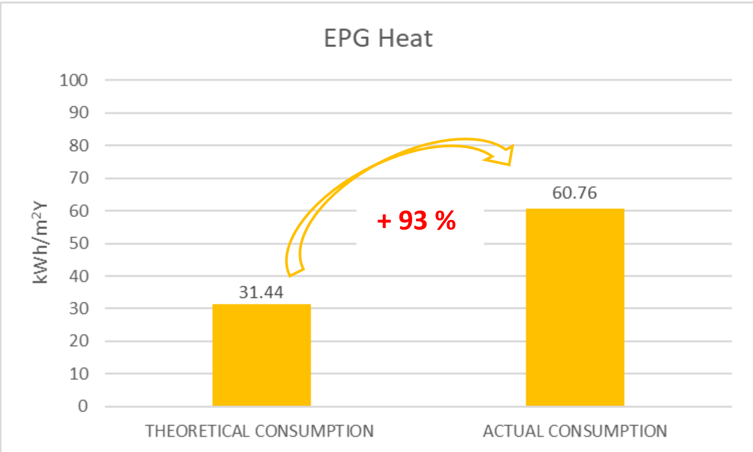


Figure 52: Energy Performance Gap - Heating

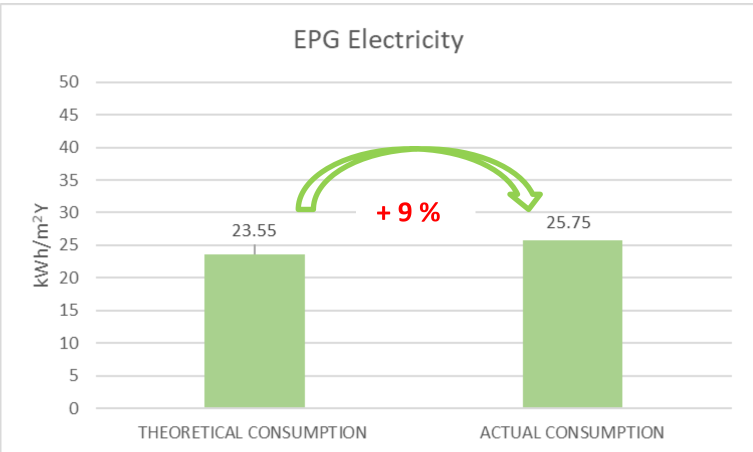
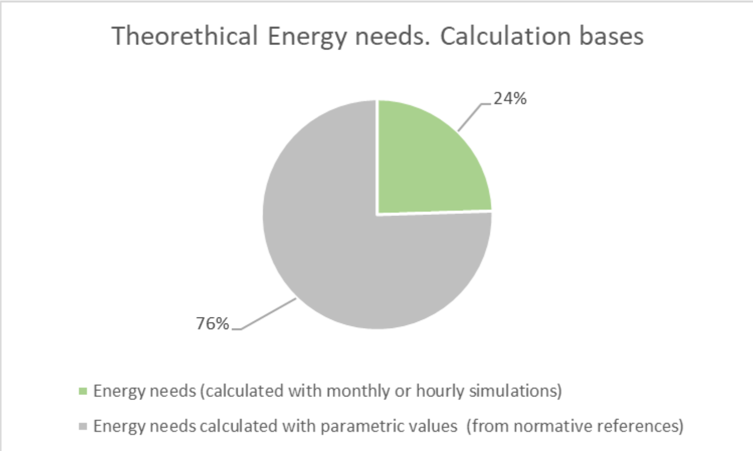


Figure 53: Energy Performance Gap - Electricity

COMMENTS
The calculation shows that the building requires nearly twice as much heating energy compared to the theoretical value (+ 93%), while the electricity demand is only approximately 10% higher. For the interpretation of the results it must be considered that not all the theoretical energy requirements have been calculated on a monthly or hourly basis. Instead, most of the theoretical energy consumption is calculated on a parametric or tabular basis in kWh/(m^{2}y) (based on standard SIA 380/1 and SIA 2024). The underlying reason is that some energy needs are not considered either in the Minergie certification or during the design stage (legal requirements). For example, the energy needs for lighting are not always calculated and the energy requirements for household appliances are never calculated. These values were calculated in the context of the GAPxPLORE project.    *Figure 54: The energy needs are calculated with simplified parametric values and not through simulations (monthly or hourly).*
MOTIVATIONS EPG
Based on an analysis of the Minergie design documentation, the monitored consumption values, and the Energo engineers reports, the possible reasons for the EPG (and the recommended optimizing measures) were identified and are discussed below. HEATING A measurement campaign allowed the Energo engineers to establish that the internal temperatures were 2-3 ° C higher than the standard value (20°C). They also found rapid drops in temperature, probably due to the prolonged opening of the windows. The solar blinds are frequently lowered even during the day, resulting in lower solar gains than expected.

As a measure of improvement, distribution of an information brochure with good practices for the inhabitants, concerning:

- not leaving the solar shields closed all day
- lowering the room temperature
- ventilation by window opening for shorter time

The hot water boiler is operating 24/24 without time scheduling: adjust time schedules and lower the delivery temperature of the boiler from 55 °C to 50 °C.

The heating load curve is high: decrease the heating load, lower the setpoint temperature of the primary circuit from 95 °C to 75 °C.

ELECTRICITY

A more efficient control of the ventilation systems is possible by time-dependent speed adjustment. The same kind of adjustment can be applied to the circulation pumps for heat distribution.

BUILDING 2	
Year	2016
A_e	1’181 m^2
Housing	1030.5 m^2
Office	150.5 m^2
Heating	
100%	GEOTHERMAL HEAT PUMP
Hot water	
100%	GEOTHERMAL HEAT PUMP
PV	
64	kWp (not considered in Minergie)
data from Minergie	

THEORETICAL CONSUMPTION		
Building 2	**Heat**	**Electricity**
HEATING	33’658 kWh	
HOT WATER	22’439 kWh	
VENTILATION		718 kWh
COOLING		0 kWh
AUXILIARIES		487 kWh
LIGHTING (housing)		4’724 kWh
LIGHTING (office)		3’450 kWh
APPLIANCES (housing)		14’427 kWh
APPLIANCES (office)		2’850 kWh
Total THEORETICAL	**56’097 kWh**	**26’656 kWh**
	47.50 kWh/m^2	22.57 kWh/m^2

ACTUAL CONSUMPTION		
Building 2	**Heat**[4]	**Electricity**
2016	69’514 kWh	45’146 kWh
2017	66’830 kWh	45’800 kWh
Total average ACTUAL	**68’172 kWh**	**45’473 kWh**
	57.72 kWh/m^2	38.50 kWh/m^2

[4] Is considered the heat delivered to the building, energy supplied by the heat pump (at the condenser)

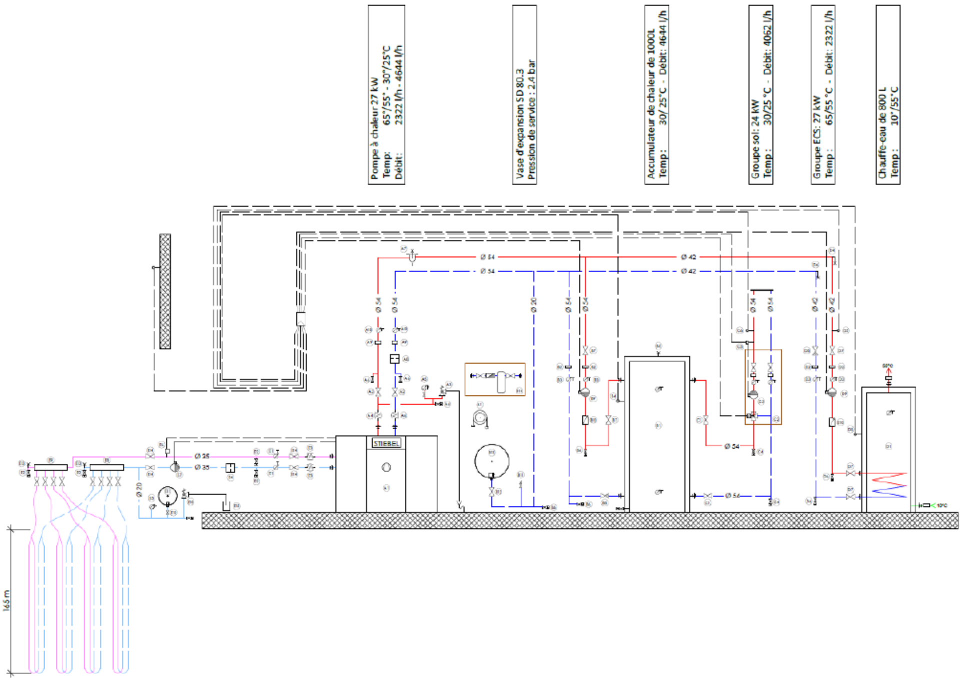


Figure 55: Heating System layout. Source: Energo

Figure 56: Annual evolution of energy consumption (Heat, Electricity). Source: Energo

ENERGY PERFORMANCE GAP				
	Heat		**Electricity**	
Total THEORETICAL	**56’097 kWh**		**26’656 kWh**	
	47.50	kWh/m^2	22.57	kWh/m^2
Total average ACTUAL	**68’172 kWh**		**45’473 kWh**	
	57.72	kWh/m^2	38.50	kWh/m^2
EPG	**+ 21.52 %**		**+70.59 %**	

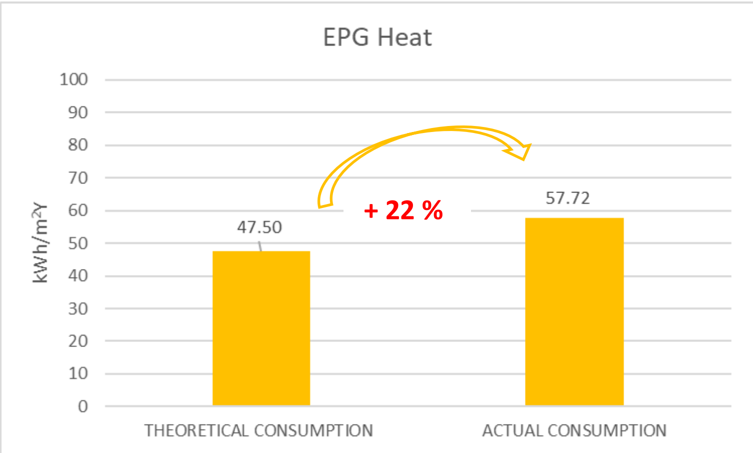


Figure 57: Energy Performance Gap – Heating

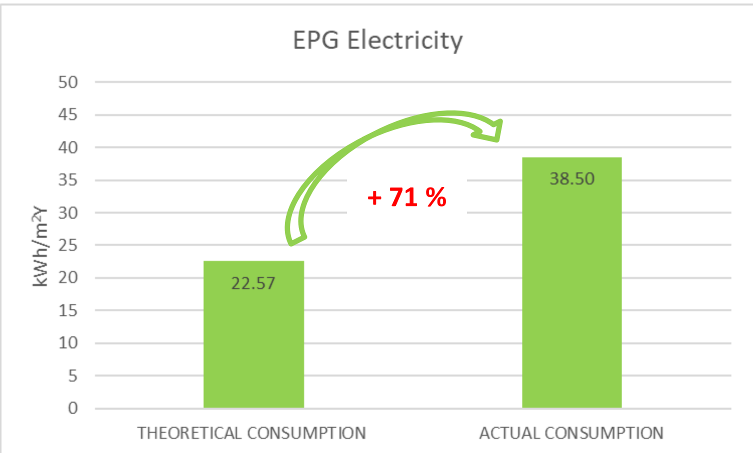


Figure 58: Energy Performance Gap - Electricity

COMMENTS
The calculation shows that the building presents an EPG for the heating at + 22%, while the electricity demand is about 71% higher. For the interpretation of the results it must be considered that not all the theoretical energy requirements have been calculated on a monthly or hourly basis, most of the theoretical energy consumption is calculated on a parametric or tabular basis in kWh / m^2 (based on standard SIA 380/1 and SIA 2024). This is because some energy needs are not considered either in the Minergie certification or during design (legal requirements). For example, the energy needs for lighting are not always calculated. The energy requirements for household appliances are never calculated. These values were calculated in the GAPxPLORE project.

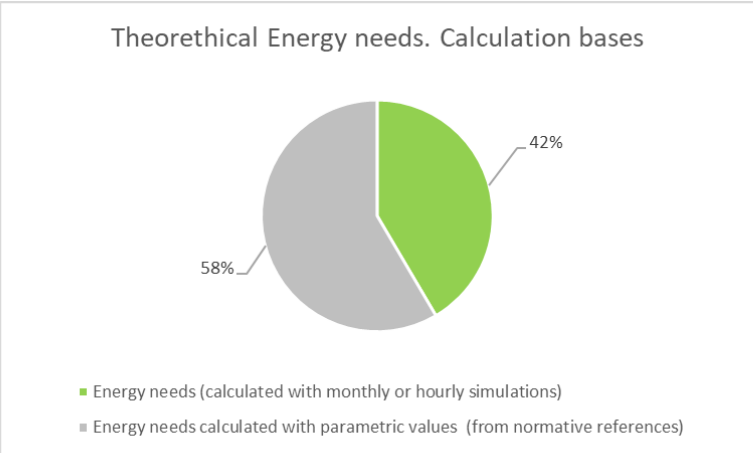


Figure 59: The energy needs are calculated with simplified parametric values and not through simulations (monthly or hourly).

MOTIVATIONS EPG
After viewing the Minergie design documentation, the monitored consumption values, and the Energo engineers reports, the possible motivations of the EPG (and the recommended optimizing measures) are shown below. HEATING From a measurement campaign in three apartments, the Energo engineers found that the internal temperatures were higher than the standard value (20°C), an average of 23.5 °C. They also found rapid drops in temperature for 1-1.5 hours, probably due to the prolonged opening of the windows. • Lower the heating delivery load curve (day and night). • Opening windows for shorter time (5-10 min. and close). ELECTRICITY About 70% of actual energy consumption is due to common energy consumption (ventilation system, common lighting, etc). Check the regulation of the ventilation system fans and other devices that could cause such consumption as circulation pumps or similar.

BUILDING 3	
Year	2012 (renovation)
A_e	1'240 m^2 (Office)
Heating	
100%	GEOTHERMAL HEAT PUMP
Cooling	
100%	GEOTHERMAL FREE COOLING
Hot water	
100%	GEOTHERMAL HEAT PUMP
PV	
4.4	kWp
data from Minergie	

THEORETICAL CONSUMPTION		
Building 3	**Heat**	**Electricity**
HEATING	74'000 kWh	
HOT WATER	8'556 kWh	
HEATING[5]		24'000 kWh
HOT WATER[6]		3'168 kWh
VENTILATION		0 kWh
COOLING		10'217 kWh
COOLING SERVER		25'832 kWh
SERVER		26'638 kWh

[5] Electricity absorbed by the heat pump with a standard annual efficiency of 3.1 (Standard value Minergie)

[6] Electricity absorbed by the heat pump with a standard annual efficiency of 2.7 (Standard value Minergie)

LIGHTING (office)		22’099 kWh
APPLIANCES (office)		22’838 kWh
Total THEORETICAL	**82’956kWh**	**134’794kWh**
	66.90 kWh/m^2	108.71 kWh/m^2
	ACTUAL CONSUMPTION	
	Heat[7]	**Electricity**
2014	47’488 kWh	134’162 kWh
2015	43’063 kWh	141’334 kWh
2016	44’119 kWh	129’990 kWh
2017	50’301 kWh	117’946 kWh
Total average ACTUAL	**46’242 kWh**	**130’858 kWh**
	37.29 kWh/m^2	105.53 kWh/m^2

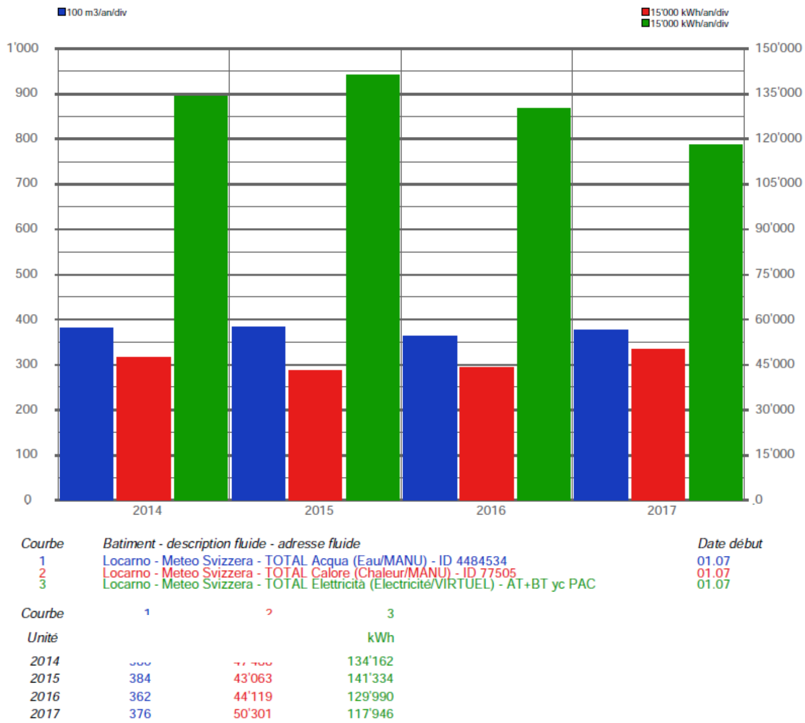


Figure 60: Annual evolution of energy consumption (Heat, Electricity, Water). Source: Energo

[7] Is considered the heat delivered to the building, energy supplied by the heat pump (at the condenser)

ENERGY PERFORMANCE GAP		
	Heat	**Electricity**
Total THEORETICAL	**82'956kWh**	**134'794kWh**
	66.90 kWh/m²	108.71 kWh/m²
Total average ACTUAL	**46'242 kWh**	**130'858 kWh**
	37.29 kWh/m²	105.53 kWh/m²
EPG	**-44.26 %**	**- 2.92 %**

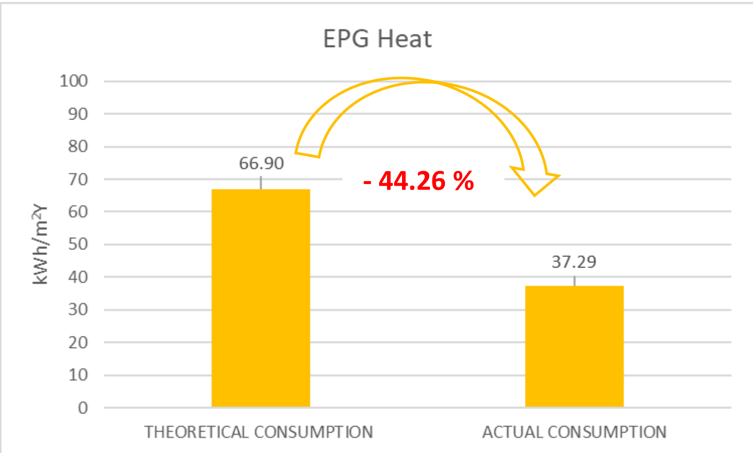


Figure 61: Energy Performance Gap – Heating

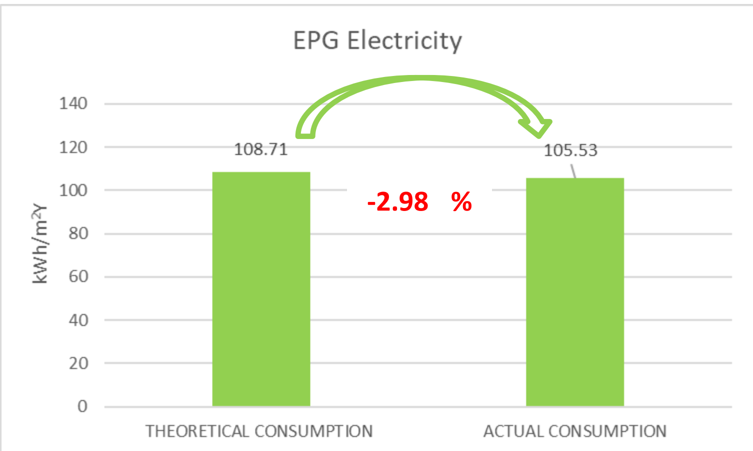


Figure 62: Energy Performance Gap – Electricity

COMMENTS
The calculation shows that the building presents an EPG for the heating at – 44.26%, while the electricity demand is about -2.98 % lower. It should be noted that in this case the energy requirement for powering the heat pumps is included in the electricity demand for electricity. Therefore, given that the EPG in electricity consumption is negligible, it may be possible to deduce that lesser energy needs for heating is offset by higher electricity consumption for other uses. For the interpretation of the results it must be considered that not all the theoretical energy requirements have been calculated on a monthly or hourly basis, most of the theoretical energy consumption is calculated on a parametric or tabular basis in kWh/m^2 (based on standard SIA 380/1 and SIA 2024). This is because some energy needs are not considered either in the Minergie certification or during design (legal requirements). For example, the energy requirements for household appliances are never calculated. These values were calculated in the GAPxPLORE project.

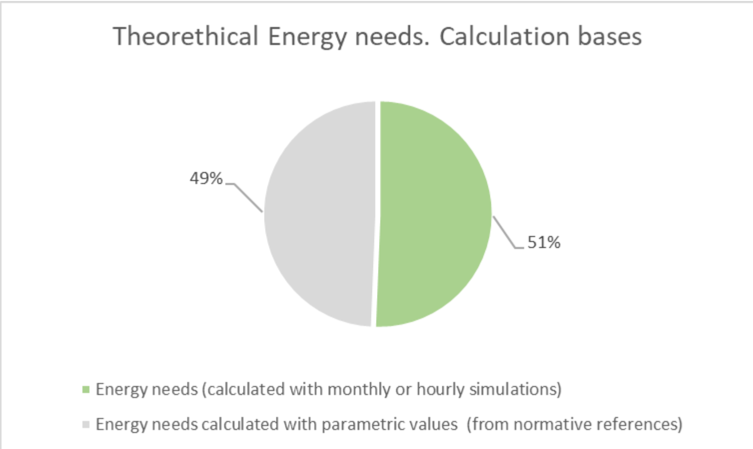


Figure 63: The energy needs are calculated with simplified parametric values and not through simulations (monthly or hourly).

MOTIVATIONS EPG
After viewing the Minergie design documentation, the monitored consumption values, and the Energo engineers reports, the possible motivations of the EPG (and the recommended optimizing measures) are shown below. HEATING The heat demand of the building is lower than expected, probably due to a pessimistic evaluation of the floor U transmittance (U value of 3.0 W/m^{2}K) and due to the fact that the transmittances of the construction elements were determined by catalogues and not by calculation. In this building the Energo engineer has decreased the heating curve, and lowered the temperature of the heating circuit. ELECTRICITY The building is characterized by high electricity consumption probably due to the presence of a large server (cooled) and the presence of many computers. The cooling of the server can be optimized with a better circulation of cold air thanks to plastic curtains.

BUILDING 4

Year	2015
A_e	1’910 m^2 (Office)
Office	1’621 m^2
Public room	289 m^2
Heating	
100%	GEOTHERMAL HEAT PUMP
Cooling	
100%	GEOTHERMAL FREE COOLING
Hot water	
66.4%	GEOTHERMAL HEAT PUMP
33.6%	SOLAR THERMAL (10 m^2)
PV	
20 kW$_p$ (not considered in Minergie)	

data from Minergie

THEORETICAL CONSUMPTION

Building 4	**Heat**	**Electricity**
HEATING	46’158 kWh	
HOT WATER	15’280 kWh	
VENTILATION		9’038 kWh
COOLING		2’623 kWh
LIGHTING		13’496 kWh
APPLIANCES		36’290 kWh
Total THEORETICAL	**61’430 kWh**	**61’447 kWh**
	32.17 kWh/m^2	32.17 kWh/m^2

ACTUAL CONSUMPTION		
	Heat[8]	**Electricity**
2015	125’778 kWh	135’723 kWh
2016	120’441 kWh	143’916 kWh
2017	107’415 kWh	149’174 kWh
Total average ACTUAL	**117’878 kWh**	**142’937 kWh**
	61.72 kWh/m^2	74.84 kWh/m^2

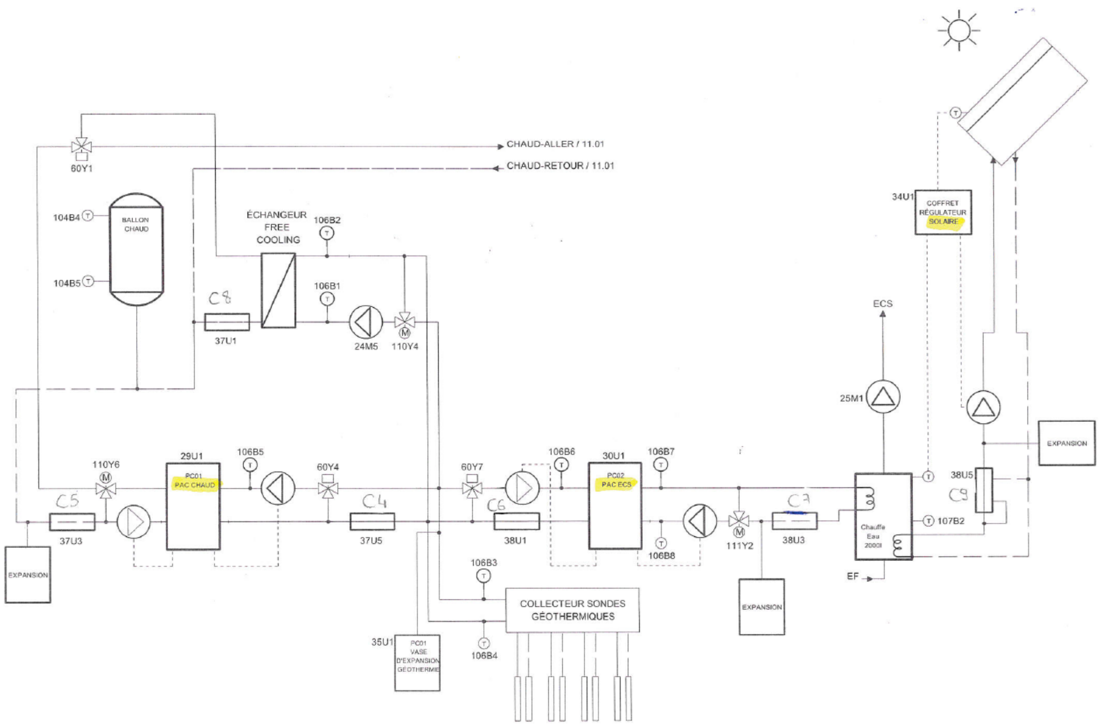
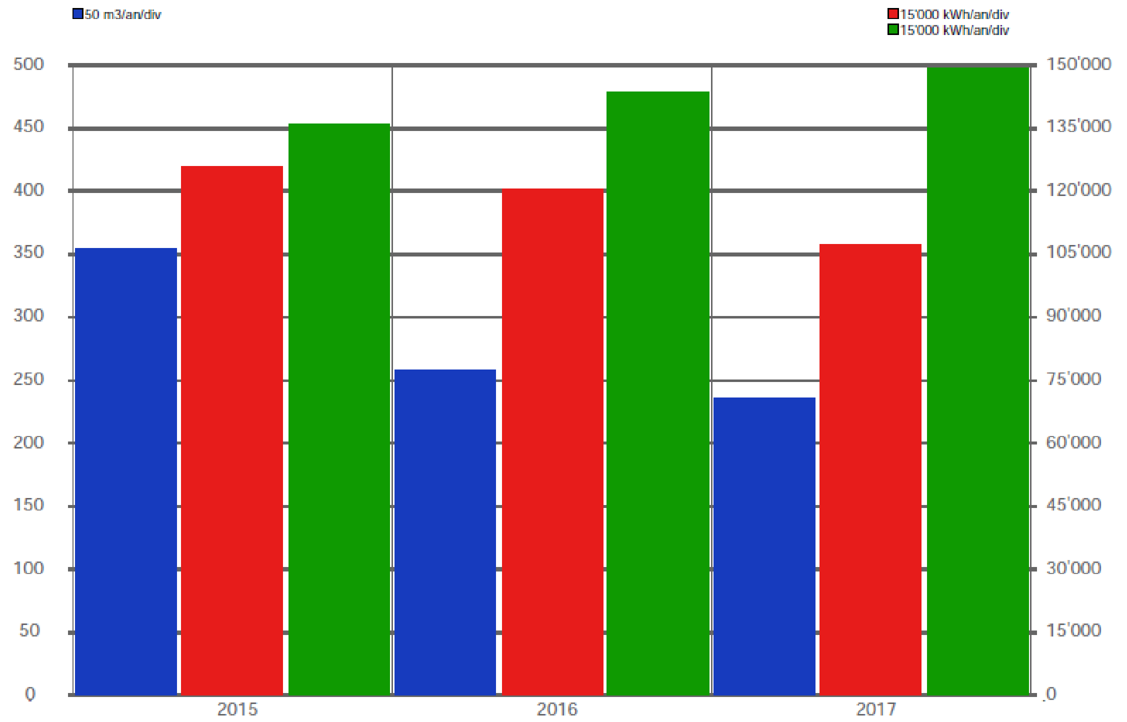


Figure 64: Heating System layout. Source: Energo

[8] Is considered the heat delivered to the building, energy supplied by the heat pump (at the condenser)



Courbe	Batiment - description fluide - adresse fluide	Date début
1	L: 'AL EAU (yc arrosage) (Eau/VIRTUEL) - Adresse GTC	02.12
2	L: 'AL Chaleur (Chaleur/VIRTUEL) - ECS+Chauffage PAC	02.12
3	L: 'AL EL (Electricité/VIRTUEL) - Réseau + PV	30.11

Courbe	1	2	3
Unité	m3	kWh	kWh
2015	353	125'778	135'941
2016	258	120'441	143'608
2017	235	107'412	149'278

Figure 65: Annual evolution of energy consumption (Heat, Electricity). Source: Energo

ENERGY PERFORMANCE GAP		
	Heat	**Electricity**
Total THEORETICAL	**61'430 kWh**	**61'447 kWh**
	32.17 kWh/m^2	32.17 kWh/m^2
Total average ACTUAL	**117'878 kWh**	**142'937 kWh**
	61.72 kWh/m^2	74.84 kWh/m^2
EPG	**+ 91.86 %**	**+132.62 %**

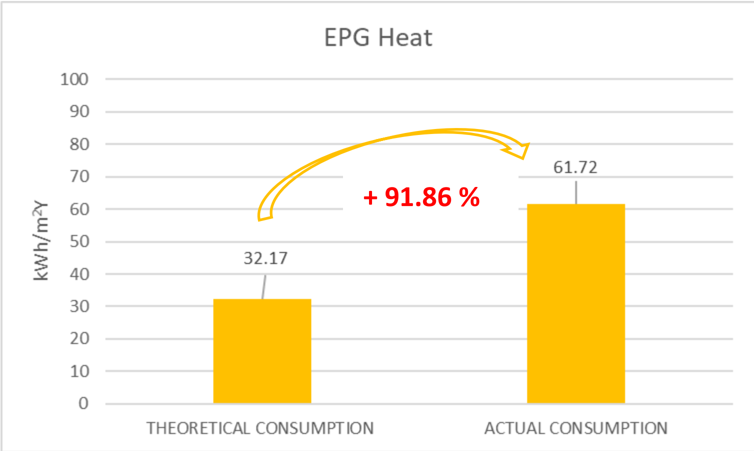


Figure 66: Energy Performance Gap - Heating

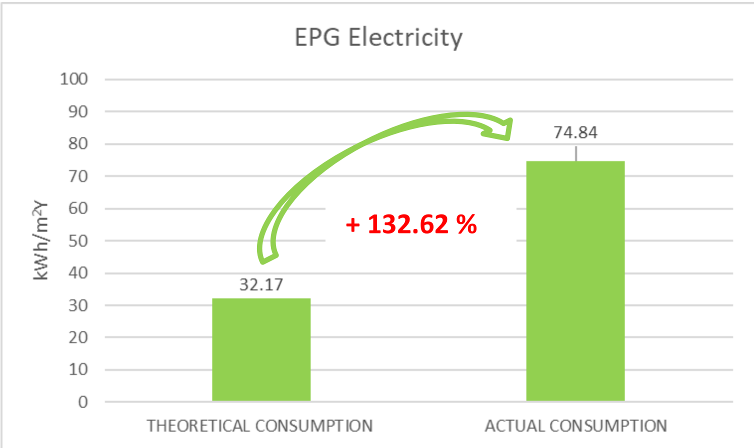


Figure 67: Energy Performance Gap - Electricity

COMMENTS

The calculation shows that the building presents an EPG for the heating at + 91.86%, while the electricity demand is about 45.60% higher.

For the interpretation of the results it must be considered that not all the theoretical energy requirements have been calculated on a monthly or hourly basis, most of the theoretical energy consumption is calculated on a parametric or tabular basis in kWh/m^2 (based on standard SIA 380/1 and SIA 2024).

This is because some energy needs are not considered either in the Minergie certification or during design (legal requirements). For example, the energy needs for lighting are not always calculated. The energy requirements for household appliances are never calculated. These values were calculated in the GAPxPLORE project.

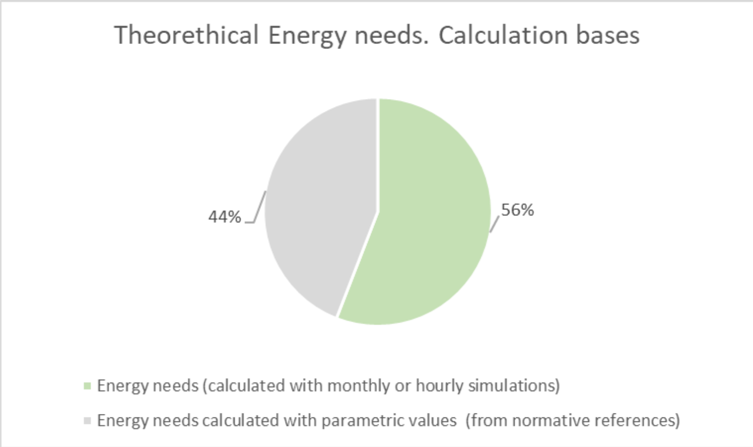


Figure 68: The energy needs are calculated with simplified parametric values and not through simulations (monthly or hourly).

MOTIVATIONS EPG

After viewing the Minergie design documentation, the monitored consumption values, and the Energo engineers reports, the possible motivations of the EPG (and the recommended optimizing measures) are shown below.

ELECTRICITY

An EPG regarding electricity consumption can partly be explained by the fact that in some rooms (corner rooms) electric heaters are installed. The electric heaters were installed due to the modification of the internal partitions of the rooms.

From measurements concerning the rooms CO_2 content [ppm], it was found that the CO_2 was very low (between 400 and 800 ppm), while it could reach a value up to 1400 ppm. Moreover, the ventilation system works constantly from Monday to Sunday.

- Decrease the air flow rates of the ventilation system.
- Adjust the operation of the ventilation system according to the times and days of presence of users.

HEAT

Greater consumption can be caused by excessive air volumes or operation of the ventilation system.

Air tightness problems are reported in the area of the frames and openings that generate a feeling of cold in the occupants.

Some optimization actions have been identified:

- Reduction of the heating curve by 2-3°C, and activation of the night reduction of at least 10 °C.
- Heating Timetable adjustment (introducing night reduction).

7.5 Discussion and Conclusion

This section aimed to quantify the performance gap between theoretical and actual consumption while trying to determine the causes of this gap. The four cases analysed in this section may be considered as best cases both in terms of the availability of theoretical consumption (from Minergie documents) and monitored consumption data and for the availability of a detailed analysis of the behaviour of the building through the Energotools platform that highlights the optimization work of an accredited engineer.

In this section, it was found that a significant source of uncertainty in calculating the buildings' EPG was the detailed calculation of the theoretical consumption. For the buildings analysed, theoretical consumption was calculated using a mix of rough yearly consumption indexes (given in kWh /m^2y) and more detailed time-series (e.g. hourly, monthly) calculations for certain building systems – however for the latter there was a mix of approaches for the calculation rather a single unified approach. This mix of methods introduces additional uncertainties in the theoretical consumption calculation. In the 4 cases analysed (Figure 69), between 44% and 76% of the theoretical consumption were calculated with yearly indices and the remaining energy consumption are calculated in a more precise but non-homogeneous way. This is because the calculation of the theoretical consumption for the various building systems (heating, ventilation, lighting, etc) is performed as part of the building design and certification process, i.e. to demonstrate compliance of the individual systems with building norms and specific requirements of buildings labels such as Minergie, as well as to validate design choices. These theoretical consumption calculations are not performed as part of a holistic approach for forecasting whole building consumption.

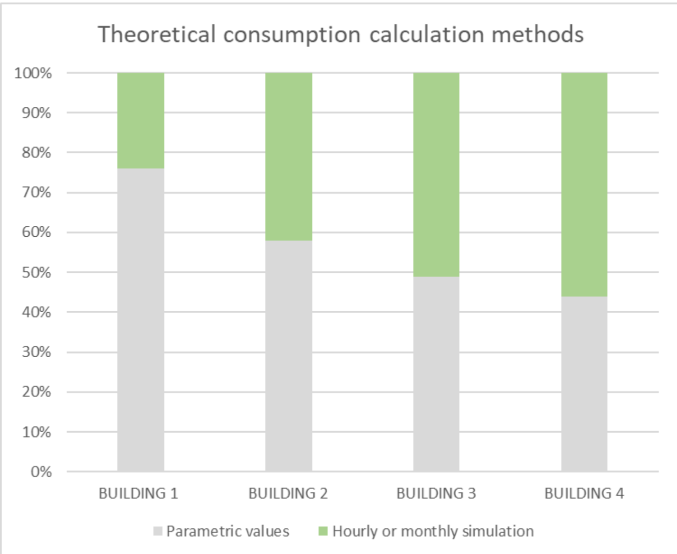


Figure 69: Between 44% and 76% of the theoretical consumption were calculated with parametric indices and the remaining are calculated in a more precise but non-homogeneous way.

The four case studies displayed very different behaviours. The heating performance gap ranged from -44% to +93%. In residential buildings, the indoor temperature (22 -23°C) was generally around +2-3°C higher than the standard of 20°C. Users also ventilate manually by opening windows for longer than expected, causing temperature drops and increasing the energy consumption for heating. For all buildings, it was possible to optimise the heating systems by adjusting the heating supply curves, thereby limiting temperatures and reducing the performance gap. The electricity consumption EPG ranged from -2.93% to +132% (Figure 70). Two main causes were identified. Firstly, the schedules of the ventilation system and air flow rates did not match the building occupancy and were therefore sub-optimal. Secondly, appliances were found to have high electricity consumption compared to expectations particularly in administrative (office) buildings.

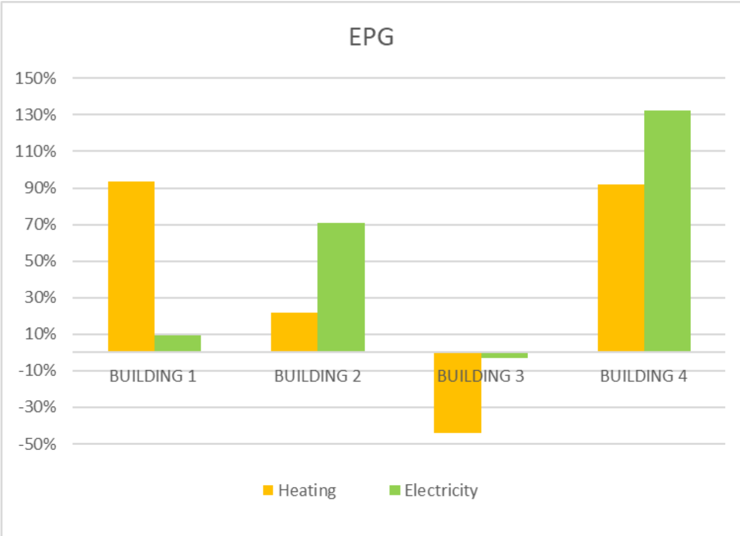


Figure 70: Determined EPG for each building considering the energy needs for heating and electricity.

Table 23: Case studies - Summary of results.

Building	EPG [%]		Calculations [%]	
	Heating	Electricity	Parametric values	Hourly or monthly simulation
Building 1	93.3	9.36	76	24
Building 2	21.5	70.6	58	42
Building 3	-44.3	-2.92	49	51
Building 4	91.9	132.6	44	56

Identification of the causes of the failure of the studied buildings to meet expected performance levels required continuous monitoring over several years combined with ongoing interventions from an energy consultant. Determining the causes is complex because they depend on different related to several phases of the building's life cycle (design, construction, utilization, etc.). This highlights the need for the correct selection of energy consumption indexes for the calculation of theoretical consumption. However, actually addressing the performance gap in an existing building can only be done during its operational phase, for which actual data on energy consumption are available.

To address the performance gap, minimally invasive optimisation of the building systems (regulation of temperatures and flow rates in heating systems, ventilation operating times, etc.) can be performed, offering a cost-effective way to reduce energy consumption. These interventions work by addressing mal-functioning or incorrectly configured systems in a first instance, and in a second instance by better matching the operation of the systems with the real use of the buildings. The latter aspect of the interventions furthermore addresses the gap between the theoretical consumption calculated based on standard use and consumption based on real use.

8 Limitations

It is important to note the minimum and maximum values in Figure 21, which show that the energy consumption of some buildings is actually very different than expected. This spread of values also demonstrates that there is a strong overlap in final energy use across the ratings. This means that using only the energy rating based on theoretical calculation as predictor of actual energy consumption is subject to high uncertainty. The finding for the entire Swiss residential building stock, according to which the performance gap after retrofit is only 2.11% (i.e. actual consumption slightly larger than calculated), is reassuring but it is in contrast to some previous studies relying on case studies in Switzerland. Our finding is based on a sample from the CECB and further research would be required to understand whether the buildings included in this sample perform better than average in Switzerland.

More generally, a concern with the CECB is related to the influence of human error of the CECB Experts when evaluating buildings and compiling certificates. A study of ESTIA (2013) studied this potential influence, asking eight experts to produce a certificate for the same buildings given the same information and instruments. The main finding was that the experts repeated the same errors in different analysis, however these led to the assignment of different energy labels (D instead of C) in only one case. Under the assumption that this small sample is representative, the inspectors' influence can be considered irrelevant for the overall distribution of the energy labels. However, the sample size of eight experts is too limited to draw any general conclusions. Another problem is related to the nature of the CECB Expert itself. Most of these persons are certifiers on the basis of a licence obtained within a single-day course, but often have no experience on a construction site. Therefore, they may have little knowledge of the problems that can arise during the construction process. This lack of training of the certifiers may contribute to the gap between the performance calculated in the certificate and the actual performance obtained by the building. The poor qualification of the expert is partially linked to the sudden need of this role. For example, only a handful of experts were active in the canton of Geneva until 2017, when the CECB was made compulsory to apply for subsidies of more than 10 000 CHF. Two years later (2019), there are already 65 CECB experts for Geneva. It is therefore important to continue training these experts and it may be necessary to combine a renewal of their role as CECB expert with more demanding exams. As further constraining factor, the time assigned to a CECB expert is very limited in order to leep the cost low; it amounts to 8 hours for preparing a regular CECB file and 14 hours for a CECB+ file. This very tight time budget makes cross-checks practically impossible and may force the CECB experts to make simplified assumptions.

Another source of uncertainty related to the CECB database is the acquisition of the actual energy data. For most existing buildings, heating consumption data are available over several years. The CECB Expert must request this data for a minimum of three years from the building owner and calculate an average of them. It is important to note that the accuracy of the actual consumption data and any cross-checking are entirely under the Expert's responsibility, neither the online tool nor any authorities can check them. On a cantonal level, the authorities handling the CECB reports in the context of subsidy requests can reject a report considered not reliable or insufficient. A quality check program has been initiated in 2017 on a nationwide scale, not only to evaluate the quality of the certificates generated, but also to help the Experts to improve their skills and to optimize the online tool itself.

The large number of buildings in the datasets used in this study is a significant advantage but also presents certain limitations. The operations of filtering and cleaning the data were already discussed in Section 3.2, nevertheless even in the final sample used in the analyses there is a large range of magnitudes of actual energy consumption for buildings with identical energy rating. This phenomenon could be due to the presence of secondary or holiday houses, which are mostly vacant, and therefore have an actual yearly consumption which is very different from the theoretical. Unfortunately, in these cases it has not been possible to determine if the difference was due to a larger performance gap or the limited use of the building, or to incorrect information in the certificate. In addition, the process of filtering implies uncertainties. For example, as explained in Section 5.3, of the 10 178 buildings with both multiple CECB versions and actual energy consumption values, three quarters had the same energy performance as before; since the numerical value of energy demand is identical to the pre-retrofit state it seems plausible to assume that no retrofit was performed. Among the remaining buildings, the energy performance deteriorated for a few (12 buildings) whereas 403 buildings were considered as outliers and removed for this reason. While these filtering rules are plausible and may be fully justified for this dataset, other studies have shown that the energy performance of buildings for which energy retrofit subsidies have been requested may not improve or may even slightly deteriorate (confidential study). In many cantons, the CECB is a requirement for requesting subsidies. It is a key problem that the CECB is not compiled at the beginning of the project, and then followed during the project execution/construction, but that it is instead prepared only at the end of the design stage, in order to validate the choices made. When the CECB is done, the architect has already made his decisions (after almost one year of work) and the systems engineer has already sized the installation, making it very unlikely that any alternative solution proposed by the CECB Expert can be integrated into the project. The architect has hence a much higher level of influence and incurs much higher cost than the energy expert (CECB cost between 1000 and 2000 CHF while the cost of the architect is on average 10/15% of the total cost of the retrofit). Under these circumstances the CECB expert may find himself/herself having no other choice than accepting the project (even if the energy efficiency indicators could still be improved). The CECB should be instead realized at the beginning of the design, to be really integrated in the process, to optimize the consumption, and minimize the EPG. This would, however, incur clearly higher cost. The role of the CECB in the subsidies process is also of considerable importance and should be taken into account when interpreting the results of this work: before starting a building retrofit, the project is presented to the authorities and a part of the subsidies is paid according to the expected label improvement (e.g. in Geneva an improvement by two label steps entitles the owner of an SFH to a subsidy of 75 CHF/m^2 and to even 115 CHF/m^2 for an improvement by three label steps (Republique et Canton de Geneve, 2017)). This type of practice may have biased the dataset resulting in a higher anticipated energy label level than what is actually achieved after retrofitting. Unfortunately, to date, there is a lack of effective control over the actual achievement of the energy objectives set: while the sample of the dataset used for studying the effectiveness of energy retrofitting does contain the energy use before and after the new label was assigned it is not known what the target efficiency of the renovation was (e.g. two label steps while only one was achieved). This is a clear deficit of the system as it is currently implemented. Also for our analysis using CECB data it is a major limitation that there is no monitoring and controlling of the performance after the certificate has been issued. In this way it becomes very difficult to assess the outcome of retrofit and to identify, and possibly close, the EPG.

Moreover, given the limited number of A-label and high-performance buildings in this work, the results from their analysis should be treated with caution. A different dataset containing more highly efficient buildings would be required to better understand the EPG in this kind of building (the Swiss Solar Agency dataset analysed within this study may be biased considering that these are all buildings receiving awards for their energy performance; and the Minergie dataset studied is rather small).

9 Final conclusions and outlook

This project has investigated the Energy Performance Gap (EPG), defined as the difference between theoretical and actual energy consumption of a building, in the Swiss residential sector. Large-scale datasets based on the Cantonal Energy Certificate for Buildings (CECB), in combination with data from the Swiss Solar Agency, Energo and Minergie, have been used for the analysis, making this study the most comprehensive so far conducted in Switzerland.

The overarching research question of the GAPxPLORE project was to establish whether and to what extent an EPG exists in residential buildings in Switzerland. This led to the subsequent questions of how the EPG is distributed among the different building typologies (performance level and age). In addition to the study of the performance gap, GAPxPLORE also investigates the Energy Savings Deficit (ESD), defined as the difference between the expected and achieved reduction in energy consumption in renovated buildings. In terms of scope, the primary focus lies on the final energy consumed for heating and domestic hot water in residential buildings, following a similar approach as previous performance gap studies.

Before embarking on the quantitative analysis of EPG and ESD, a literature study was conducted, covering both the national and international state of the art regarding performance gap. The review of existing research has shown that there are a number of different definitions for calculating the EPG, and a large range of values reported. Three interpretations have been identified, distinguishing the way how the calculated consumption (for subsequent comparison with the actual consumption) is modelled: a regulatory, static, and dynamic performance gap. The regulatory performance gap, that compares the performance of a building under standardized national conditions to measured energy use, is the most widely used type of EPG and it plays an important role in this study as well. This variety in metrics and terminology and the resulting challenge of drawing sound conclusions has been identified as an obstacle to close the EPG, since it must be very clear what is included in the consumption values that are compared and what type of energy is compared (i.e. heating demand or final energy for the full uses of the building). There is some lack of clarity in Swiss literature and legislation, raising questions about the magnitude of the EPG. The inhabitant or the building owner is consuming and paying final energy (as measured at the meter), while the theoretical values used for comparison are given in terms of “weighted final energy”. The latter is calculated using national factors which are collectively defined by the cantons and which reflect the energy policies of each canton and of the Confederation.

The analyses of the CECB dataset confirmed the existence of an EPG for residential buildings, with a median of -11% (i.e. the median building performs slightly better than expected). This implies that, for the entire residential stock, the actual consumption of final energy is 6% lower than the predicted value. The latter result (-6%) differs from the median EPG (-11%) due to weighting of the EPG values per building by the total ERAs of the building class, and the specific energy consumption per meter square. A strong correlation was found between energy label and EPG. For low performing G-labelled buildings, a negative EPG of -40% was determined, while for the higher performing buildings with B-label, a positive EPG of +12% was determined. These results imply that higher performance buildings are consuming somewhat more than predicted while lower performance buildings are consuming significantly less than predicted. The trend for A-label buildings is less clear. However, the results concerning the A-label buildings should be treated with caution, as these buildings were poorly represented in the CECB sample: only 156 buildings with A-label were present in the dataset, equal to the 0.5% of the total sample. Although many buildings showed a positive EPG the median was negative (-6.2%).

It is important to highlight that the different values of the EPG found between low and high-performance buildings lead to very different impacts on the final energy consumption, as one percent point represents very different energy consumption values in terms of kWh/(m^{2}y) for the low rating compared to the high rating. For example, in label E an EPG of -15% corresponds to a difference between actual and theoretical of -27 kWh/(m^{2}y), while in label B a similar EPG (with inverse sign) of +12% corresponds to an absolute difference of only +8 kWh/(m^{2}y). Therefore, care should be taken when considering the percentage values for EPG for different energy labels because of the differing real impact on total final energy consumption. This is further highlighted when considering retrofits. The EPG values just mentioned are smaller than those reported in existing case studies in Switzerland. This is partly caused by the fact that this is the first stock-level assessment (rather than focusing on small numbers of high efficiency buildings). A further reason may be that building owners applying for a certificate may pay more attention to energy efficiency than the average owner. Finally, the subsamples of the CECB data used for this analysis may not be fully representative of the Swiss building stock for other reasons (e.g. cantonal representation, filtering etc.). A similar pattern to the one established for the EPG as a function of the energy labels was found for CO_2 emissions. An important finding is that the emission intensities in terms of kg CO_2-eq per kWh of final energy consumed are very similar among the labels between C and G, showing a large drop only for the labels A and B. This highlights the contribution of the low emissions of the heating systems installed in these new or deeply renovated buildings, and further indicates a need for energy policy to incentivise reducing carbon emissions in addition to requiring a minimum level of energy efficiency.

A subsample of the CECB dataset was then generated which consisted of residential buildings that had a CECB certification both before and after renovation in order to investigate the relationship between the expected and achieved savings obtained through energy retrofit. This subsample included 1172 buildings. For all these buildings, the Energy Savings Deficit was calculated. Two versions of the ESD have been proposed in this study: the regulatory ESD (ESDr) defined using the theoretical savings (based on theoretical energy consumption before and after retrofit) as the expected savings, and the anticipated ESD (ESDa) using the anticipated savings (difference between actual consumption before retrofit and theoretical consumption after retrofit) as the expected ones.

The ESDr and ESDa were calculated for the whole subsample, resulting in a median ESDr of 37.3% and a median ESDa of 3.60%. The result for the ESDr implies that based on the theoretical values, only 62.7% (100% – 37.3%) of the expected savings are actually achieved. Instead when using the anticipated values (ESDa), 96.4% (100% - 3.60%) of the expected savings are actually achieved. These results suggest that the ESDr is not a useful indicator to evaluate the success of an energy retrofit, as most of the shortfall in energy is due to an over-estimation of the consumption of the building before the retrofit. Therefore, the ESDr it not appraising the quality of the retrofit itself, as is it biased from an error in the calculation of the maximum (theoretical) savings achievable. Conversely, the anticipated energy savings deficit (ESDa) proves to be a clearly more reliable indicator for judging the success of a retrofit in view of the small error in absolute terms (only 3.60%). The ESDa has the additional benefit that significant deviations between Anticipated and Actual savings indicate system or operational failures (i.e. if the building does not perform as anticipated, this is likely related to a practical issue rather than an error in the calculation). Finally, the small value of ESDa found suggests that the overall quality of the energy retrofitting performed within this sub-sample is high, indicating, *inter alia*, that on-site workmanship is not a major problem in Switzerland.

Independently of the calculation method, it was found that despite an increase of the heated area by 7% in the course of energy retrofit, total final energy use and CO_2 emissions for thermal purposes was halved in the building sample. This analysis furthermore positively reassures that the savings objectives are often achieved, a finding that also policymakers and investors might find encouraging while keeping in mind that this analysis was based on a relatively small subset of the CECB dataset.

The EPG in high performance buildings was studied combining data from the Swiss Minergie database and from the Swiss Solar Agency. The analysis focused on the different Minergie standards (Minergie, Minergie-P, and Minergie-A) to determine the relationship between the label type and the EPG, on a sample of 56 buildings. In this case the Minergie indexes were used as reference for the theoretical consumption (in contrast to the theoretical consumption used in previous parts of the study). The theoretical values used for the Minergie buildings represent the entire energy consumption for all the energy needs of the buildings, in order to investigate whether the Minergie buildings respect their limits or not.

The first finding was the very high performance of the buildings in the sample. The actual final energy consumption of the buildings is very low, with median values of 30 kWh/(m^2y) for new buildings achieving the MoPEC standard (60 kWh/(m^2y) for retrofit), 33 kWh/(m^2y) for new Minergie buildings (45 kWh/(m^2y) for retrofit), 29 kWh/(m^2y) for new Minergie-P (43 kWh/(m^2y) for retrofit), and 30 kWh/(m^2y) for new Minergie-A (34 kWh/(m^2y) for retrofit).

Regarding the EPG, a median EPG of -14% was found, providing further support for the initial hypothesis that the most efficient buildings are more robust to the EPG. Moreover, the results 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/(m^2y) for Minergie-P buildings and by 6 kWh/(m^2y) for Minergie-A (for the total energy needs of the building). However, this finding could be partly a consequence of the small sample used (56 buildings) and its characteristics. As discussed in the Data section, these buildings are all selected in a competition that rewards the best performance, possibly explaining why the energy consumption of these buildings is in line with or lower than the standards. Moreover, inhabitants choosing to live in such high efficiency buildings may also be motivated to live low-energy lifestyles. However, the design of the Minergie-P and -A labels may be the cause of these exceptional results. The standard Minergie-A, despite having the lowest Minergie target, pays more attention to reducing the emissions per unit of energy used (e.g. by means of Photovoltaic panels) than reducing the demand, as the performance of the envelope is comparable to that prescribed in the standard Minergie label and in the MoPEC. The Minergie-P standard instead is fully dedicated to reducing the heating demand (useful heat).

Further analysis on four newly constructed Minergie buildings, resulting from the combination of the Minergie and Energo databases, revealed an extremely wide range of EPGs, varying from -63% to 352%. In terms of actual energy consumption, two out of four buildings exceed their target, one by about 80 kWh/(m^2y) and the other by 130 kWh/(m^2y), representing multiples of the Minergie target. On the other hand, the other two buildings analysed were found to be in line with their expected consumption, demonstrating that it is currently possible to achieve very ambitious energy targets. Finally, with regard to new Minergie buildings, although some exceed their limits, they remain in absolute terms buildings with excellent performance, and it is therefore recommended to continue to build in that direction (especially for the standards Minergie-P and -A). In addition, this quality label prepared the grounds for the Cantons' acceptance of even more demanding energy performance levels in the form of the MoPEC (Model of the cantons' energy regulations; see Conferenza Cantonale dei Direttori dell'Energia CDE, 2014) targets. These are unique in Europe, showing the way of how to reach buildings with a thermal energy consumption level representing only a quarter of the current building stock. A similar argument can be made for renovated buildings. In this respect too, the Minergie standards have proved their worth, especially in pushing the thermal performance required by the Cantons. In addition, the low value of the anticipated ESDa for deep retrofit (e.g. 98% of the anticipated savings are achieved for energy retrofits implying an improvement by five label steps) gives a good indication that the energy targets set before the renovation are actually met. This should therefore be an additional motivation to retrofit buildings to the highest standards. Nevertheless, the existence of a number of cases with large deviations from the median highlights the need for ongoing monitoring of buildings energy consumption, for example using smart meters.

Regarding the case studies (Section 7), the EPG for heat consumption ranged from -44% to +93% and the EPG for electricity consumption varied from -2.93% to +132%. The main reasons for the EPG for heat are i) the higher temperature of space heating and of the hot water primary circuit compared to the standard values and ii) window opening for long periods of time causing temperature drops. The main reasons for the performance gap in electricity are incorrect time schedules of the ventilation systems and high energy consumption for appliances. It was found that one of the greatest uncertainties in determining a building's EPG is not the collection of real consumption data but the determination of theoretical consumption. In the cases studies analysed, between 44% and 76% of the theoretical consumption were calculated with parametric indices and the remaining energy consumption was established in a more precise but non-homogeneous way (e.g. sometimes on an hourly, monthly or other time basis). In fact, the energy calculations carried out during the design phase of a building do not have the objective of forecasting the final total consumption but of evaluating the efficiency of the main design choices and their compliance with energy requirements by respecting the limits established by national standards or laws.

To conclude, while on the one hand a large EPG was found in old buildings, a much smaller one in absolute values was found in newer and more performing buildings, not causing significant concern about the performance of the new constructions. As highlighted in this work it is therefore crucial to use as starting point today's actual (measured) energy consumption when calculating expected future energy consumption levels. The finding for the entire Swiss residential building stock, according to which the total actual consumption of final energy is 6% lower than predicted, is reassuring but it is in contrast to some previous studies relying on case studies in Switzerland. Our finding is based on the CECB sample and further research would be required to understand whether the buildings included in this sample perform better than average in Switzerland. Similarly, the overall limited EPG found for high performing buildings is reassuring, with Minergie-P buildings even outperforming the theoretical values. In view of the origin of the data (Swiss Solar Prize) and the smaller sample size, these findings should not be generalized, while nevertheless showing that remarkably high energy efficiency levels can realistically be achieved.

The insights from this project have motivated us to further examine the causes that are behind the performance gap. In this direction, a new research project launched by SUPSI and called Positifgap is expected to provide deeper insight into the reasons behind the performance gap highlighted in the GAPxPLORE project. The project aims to identify the minimally invasive energy optimization and renovation work with the greatest impact on reducing the energy consumption of buildings, through the analysis of a single national level database made available by the Energo Association. Along similar lines, the Energy Efficiency group of the University of Geneva already started a new collaboration with the Chair of Architecture and Building Systems of the ETH Zurich. This work combines the top-down approach of GAPxPLORE with the bottom-up approach applied on several monitored case studies in order to highlight the causes of the EPG.

10 Publications

Below is a list of publications and conference papers written within the GAPxPLORE project.

Intermediate report:

- Patel K.M., Cozza S., Chambers J., Wesselmann K., Geissler A., 2017. *GAPxPLORE - Annual report 2017.* SFOE (https://www.aramis.admin.ch/Default.aspx?DocumentID=45988&Load=true)
- Cozza S., Chambers J., Gambato C., Arnold L., Patel K.M., 2018. *GAPxPLORE - Annual report 2018.* SFOE (https://www.aramis.admin.ch/Default.aspx?DocumentID=49954&Load=true)

Journal articles:

- Cozza S., Chambers J., Patel K.M., 2019. *Measuring the thermal Energy Performance Gap of labelled residential buildings in Switzerland*. Energy Policy
- Cozza S., Deb C., Chambers J., Scartezzini J. L., Schlueter A., Patel K.M., 2020. *Exploring determinants of the thermal performance gap in residential buildings through statistical analysis and in-situ measurements.* Energy and Buildings (Under review)

Conferences:

- Cozza S., Chambers J., Patel K.M., 2018. *GAPxPLORE: The building energy performance gap in Switzerland*. Status-Seminar "Forschen für den Bau im Kontext von Energie und Umwelt", 6/7 September 2018, ETH-Zurich
- Cozza S., Chambers J., Gambato C., Branca G., Geissler A., Patel K.M., 2019. *Energy consumption of high-performance buildings: Design vs. Reality*. Climate Resilient Cities Energy Efficiency & Renewables in the Digital Era. Cisbat 2019. 4-6 September 2019, EPFL Lausanne

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Appendix A – table of CECB variables

Ref. Code	Contents	Note 1	Note 2
1	Numéro de certificat CECB	Toutes les versions sont représentées, .01 à .xx	Renseignements sur le certifiat CECB. Toutes les versions d'un seul bâtiments seront listées.
2	Version CECB		
3	Date de publication CECB		
4	Station climatique		
5	Canton		
6	Catégorie de bâtiment	I à IV	Renseignements sur le bâtiment (et le type de certificat) avec l'étiquette attribuée: coeff enveloppe, années construction, SRE... Données disponibles à partir de Mai 2010 (Update outil) sur toute la Suisse avec les consommations mesurées en agents énergétiques sur les 3 dernières années, si enregistrées.
7	Date de construction		
8	Type du CECB (Type: C, CP, CN)	C="ancien" CECB depuis 2009 CP, CN= CECB Plus, calculateur avec plus de/autres détails pour tous bâtiments y.c. nouveaux projets (CN), depuis fin 2102	
9a	SRE	SRE	
9b	Coefficient d'enveloppe	coeff env.	
10	Efficacité de l'enveloppe du bâtiment (A, B, … à G)	comparaison entre deux versions de certificats possible: y a il eu rénovation, ou juste republiication pour cause de petites erreurs càd sans amélioration de l'étiquette?	
11	Efficacité de l'énergie globale (A, B, …à G)		
12a	Agent énergétique consommé antérieurement (mesuré)	y.c. unité	

12b	But antérieur (Ch / ECS / Ch+ECS/Electro)		
12c	Consommation antérieure annuelle (avec unité)		
12bis c	Autres agents énergétiques consommés antérieurement (3 colonnes resp.)		
20a	Agent énergétique/ producteur de chaleur 1 de l'état initial Ch/ECS	Dans type C (2209-2016) pas de nom d'agent énergétique à disposition	Détails sur les producteurs de chaleur pour eau chaude et chauffage avec rendements, destination (ECS, Ch ou les deux) et si disponible, date de construction du système. Chaleur solaire thermique et photovoltaïque représentée Consommation électrique séparée en électricité auxiliaire/reste conso
20b	But 1 (Ch / ECS / Ch + ECS)	Pour Ch+ECS la précision " sur l'année" ou "pendant la période de chauffe" est éventuellement disponible	
20c	Besoin adapté à l'utilisation de l'agent énergétique Ch/ECS pour but 1	Format: Ch (% ou unité) ECS (en % ou unité) "	
20d	Taux d'utilisation de producteur de chaleur 1 Ch, valeur été	für Typ G	
20e	Taux d'utilisation de producteur de chaleur 1 Ch, valeur hiver		
20f	Taux d'utilisation de producteur de chaleur 1, ECS	heisst "Winterwert" für Typ G	
20g	Taux d'utilisation de producteur de chaleur 1, ECS - distribution	für Typ G	
20h	Année mise en service du producteur de chaleur 1	Hinweis Sanierung	
21 bis 24	Autres agents énergétiques de l'état initial, 4 colonnes resp.	in G können hier nur noch Solarkollektoren vorkommen, 21c wäre aber leer. 21 a mit Label "Hilfselektrizität Solarthermie" - zB wenn 30a"ein "Ja" enthält	
30a	Utilisation énergie solaire thermique O/N		
30b	Autoproduction d'énergie de chauffage par solaire thermique (rendement)		
31	Autoproduction d'énergie électrique par PV (rendement)	type C ne dispose pas de ce renseignement	

32	Consommation électrique totale, adaptée à l'utilisation, sans énergie auxiliaire		
33	Consommation électrique totale en énergie auxiliaire	én. aux. = Tarif MT	
34a	kontrollierte Wohnungslüftung?	ja/nein (bei Typ G)	Détails géométriques et technique du bâtiment
34b	Thermisch wirksamer Aussenluftvolumenstrom	V/AE in m3/(m2h)	
35a	Lineare Wärmebrücke Wand/Decke lRW	Die Summen von WB und ihren Koeff. psi sind entweder detailliert (typ G), oderstammen aus den Zwischenresultaten (typ GP), falls dies den Aufwand des Auszuges (Zeit/Volum) begrenzt.	
35b	Koeffizient Psi RW		
35c	Lineare Wärmebrücke Gebäudesockel lWF		
35d	Koeffizient Psi WF		
35e	Lineare Wärmebrücke balkon lB		
35f	Koeffizient Psi B		
35g	Lineare Wärmebrücke Fenster lw		
35h	Koeffizient Psi WF		
35i	Lineare Wärmebrücke Boden/Wand lF		
35j	Koeffizient Psi F		
35k	Reduktionsfaktor für Lineare Wärmebrücke b WBl		
36a	Punktuelle Wärmebrücke		
36b	Koeffizient Xi		
36c	Reduktionsfaktor für punktuelle Wärmebrücke b WBp		
37a	Option : Gesamtlänge lin. WB l	Zwischenresultate Typ GP	
37b	Option: Globales Koeffizient psi		
40a	valeur u sol (contre non-chauffé/terrain)	Valeurs U pondérées par surfaces comme dans le tableau de la page 2 du certificat CECB. Surfaces commes sommées dans l'outil. Si type C et date de rénovation disponibles, les consigner dans colonne "b" respectivement Il n'y a pas de valeur g d'ensemble pour toutes les fenêtres. Les (éventuels) sols contre extérieurs sont rajoutés avec leur valeur U. Les surfaces des sols contre terrain/non chauffé et de leurs coefficients b sont issues des résultats intermédiaires par catégorie (type CP).	Détails géométriques du bâtiments selon la catégorie d'élément de construction (avec valeur U et surface), telle que représentée dans documents CECB/outil une éventuelle date de rénovation n'est possible que pour les certificats de type G, i-e l'ancien CECB existant depuis fin 2009

40b	Date rénovation sols (type C)		
40c	Surface total sols		
40d	Gesamtfläche Boden gegen Erdreich AFu		
40e	Gesamt Reduktionsfaktor bFu gegen Erdreich		
40f	Gesamtfläche Boden gegen Unbeheizt AFG		
40g	Gesamt Reduktionsfaktor bFG gegen unbeheizt		
40h	Fläche Boden gegen Aussen		
40i	U Boden g. aussen		
41a	Valeur U toit/plafond		
41b	Date rénovation toit/plafond (type C)		
41c	Surface totale toit/plafond		
42a	Valeur U murs extérieurs		
42b	Date rénovation murs extérieurs (Type C)		
42c	Surface totale murs extérieurs		
42d	Gesamtfläche Wand gegen Erdreich AWU		
42e	Gesamt Reduktionsfaktor bWU gegen Erdreich		
42f	Gesamtfläche Wand gegen Unbeheizt AWG		
42g	Gesamt Reduktionsfaktor bWG gegen Unbeheizt		
43a	Valeur U fenêtres		
43b	Date rénovation fenêtres (Typ C)		
43c	Surface totale fenêtres		
44	Datum Erstellung		
45	Datum Modifikation		
46	Datum Publikation		
50a	Kürzel pro Gebäudehüllenelement		
50b	Anzahl		
50c	Ausrichtung		
50d	Elementkategorie		
50e	Bezeichnung		
50f	b-Faktor		
50g	Fläche [m2]		
50h	Typ		
50i	g-Wert		
usw.	Glasanteil		
	Verschattung		
	Unterhaltskosten [CHF/a]		
	U-Wert[W/m2K)]		
51a	Restlicher R-Wert [m2K/W]	Schichtenaufbau (aus U-Wert Schichtenrechner)	
51b	Dämmschicht		
51c	Dicke [cm]		
51d	Widerstand [m2K/W]		
51e	Wärmeübergangswiderstände Rse+Rsi		
52a	Name	Variante	
52b	Modernisierungsart		
52c	Investition [CHF]		

52d	Berechnungsgrundlage		
52e	Unterhaltskosten [%/a]		
52f	Nutzungsdauer [a]		
52g	Zuschlagsfaktor		
53a bis 53e	Wärmeerzeuger, jeweils Bezeichnung	5 WE max, 3 VB max	Orange Zellen= Neue Daten zum Programmieren in Nov17 / New dataset in Nov 2017
54a bis 54f / …. / 56a bis 56f	Versorgter Bereich Hz (Kürzel/Bezeichnung 1 bis 3, mit jeweiliger Deckungsgrad Hz pro möglicher Wärmeerzeuger 1 bis 5)	2 Deckungsdgrad pro Versorgte Bereich	
57a bis 57f / …. / 59a bis 59f	Versorgter Bereich: Bezeichnung und jeweiliger Deckungsgrad WW pro Wärmeerzeuger	DG für HZ/WW können auch nebenaneinander im Auszug platziert werden	
(nur Titelzeile)	Endenergie pro Wärmeerzeuger und pro Energieträger im Detail :	Endenergie Ist-Zustand (Standard-Bedarf) wie Tabelle D.2.1. / D.2.2 des aktuellen Muster-Beratungsberichts	
60a bis 60h	Hilfsenergie pro WE und pro möglicher Energieträger	first 11 lines of the tabelle D.2.1.1	
	Total Hilfsenergie		
	Lüftung		
	Beleuchtung		
	Betriebseinrichtung & Geräte		
	Photovoltaïk		
	Weitere Verbraucher		
	netto gelieferte Energie		
	gewichteter Gesamtbedarf		
	nat. Gewichtungsfaktor		
	netto gelieferte P.E: gesamt		
	erneuerbare Energie		
	Kennzahl Endenergie (MJ/m2)		
	Kennzahl PE Gesamt (MJ/m2)		
	Kennzahl THG Emissionen (MJ/m2)		
61a bis 61h	Hilfsenergie pro WE und pro möglicher Energieträger	first 11 lines of the tabelle D.2.2.1 IST Zustand, effektiver Bedarf	
	Total Hilfsenergie		
	Lüftung		
	Beleuchtung		
	Betriebseinrichtung & Geräte		
	Photovoltaïk		
	Weitere Verbraucher		
	netto gelieferte Energie		
62	Belegungsfaktor	Belegungsfaktor (MFH, EFH)	

63 (Houses)	Anzahl Bewohner (EFH/ MFH) or	Hinweis im IST-Zustand, used by WIZARDS	
(Verwaltung)	Anzahl Personal	Hinweis im IST-Zustand, used by WIZARDS	
(Verwaltung)	Anzahl Arbeitsplätze	Hinweis im IST-Zustand, used by WIZARDS	
(Verwaltung)	mittlere Benutzungszeit der Arbeitsplätze in %	Hinweis im IST-Zustand, used by WIZARDS	
64 (Schulen)	Anzahl Schüler	Hinweis im IST-Zustand, used by WIZARDS	
	lichte Raumhöhe [m]	Hinweis im IST-Zustand, used by WIZARDS	
	Anzahl Vollgeschosse	Hinweis im IST-Zustand, used by WIZARDS	
	Gebäudebreite	Hinweis im IST-Zustand, used by WIZARDS	
	Bauweise Gebäude	Hinweis im IST-Zustand, used by WIZARDS	
	Grundrisstyp	Hinweis im IST-Zustand, used by WIZARDS	