Combined geospatial and techno-economic analysis of deep building envelope retrofit

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Abstract. In this study, the Swiss residential building stock model (SwissRes model) is used to conduct a geospatial analysis of the techno-economic potential of deep building envelope retrofit packages in Switzerland. Element and building characteristics of 8242 archetype buildings are combined with high-resolution spatio-temporal weather data. We estimate final energy demand before and after retrofit, while correcting for the energy performance gap. Levelized costs of energy savings are calculated in two ways, i.e. based on full costs and investment cost related only to thermal improvement of the envelope. Results show that, technically, a 57\% reduction of the final energy demand for space heating could be achieved with the deep envelope retrofit. For full costs, less than 1\% of these measures would be cost-effective, whereas for improvement costs nearly the full retrofit potential is cost-effective. We identified primarily rural and mountainous regions as well as historic city centres to show highest cost-effectiveness.

1. Introduction

It is a key objective of the Swiss Energy Strategy 2050 to substantially increase the energy efficiency of buildings. However, the current annual rate of energy retrofit is insufficient to reach the planned targets \cite{1}. It is therefore crucial to foster energy efficiency improvement of the building stock by identifying buildings that show a high energy saving potential at relatively low cost. Results from our bottom-up Swiss residential energy model (SwissRes) showed that the thermal performance can be substantially improved for certain building archetypes \cite{2,3}. An assessment of individual envelope retrofit measures demonstrated that only under very favourable economic conditions, retrofit would be cost-effective over the expected lifetime of the building elements (analysis based on total costs) \cite{4}. Significant variation in savings and economic potential across the building archetypes were found. As it is known that the distribution of archetypes across the country is not uniform, and that climate conditions also vary across the Swiss regions, it would be very beneficial for policy makers, and owners to not only have information on individual building archetypes but also their spatial distribution in a given region or city.

The aim of this paper is therefore to estimate the energy saving potential by retrofit of each individual building in the Swiss residential building stock, taking into account respective local conditions and the features of each building. The aggregated potential can then be used to pinpoint for the various energy
retrofit options locations (e.g. regions, cities or districts) with high energy efficiency potential and/or low implementation costs.

2. Methods
This study is using a bottom-up modelling approach, based on the combination of big data sources (described below) and Geographic Information Systems (GIS). In this way, each individual residential building is assigned to one of 8424 archetypes\(^1\) representing different thermal properties such as U-Values, ventilation rates as well as thermal bridges coefficients\(^2\). We derived most of this data from a database on the Swiss Cantonal Energy Certificate for Buildings (CECB)\(^5\). Whenever available, the dwelling surfaces and type of heating system reported by the official statistic was used\(^6\). The resulting energy demand of each archetype is then scaled up to the total building stock’s energy demand by accounting for the respective share of energy reference area (ERA)\(^3\). For this study we defined a deep energy envelope retrofit package based on a combination of measures applied to individual elements which we had analysed in a previous study\(^4\). In order to avoid uneconomic retrofitting, we limit ourselves to residential buildings constructed before 2000.

2.1. Energy demand simulation
For the simulation of the space heating energy demand before and after retrofit, we use the SwissRes model\(^3,4\). Given the significant energy performance gap (EPG)\(^7\) between calculated and measured consumption for certain building classes observed in our previous results, we correct for this by adjusting the standard indoor temperatures for the different archetypes (instead of using a uniform value of 20°C for all archetypes)\(^9\). This is identified in literature as one of the main factors for the EPG\(^10–12\)..

This results in lowering average indoor temperatures to 18°C for buildings constructed before 1960 (reducing consumption) and increasing indoor temperatures to 22°C for buildings constructed after 1980 (increasing consumption). This change led to a reduction of 2% for the total final space heating energy demand of the Swiss residential building stock, compared to our previous results. We assume in this study that after a deep energy retrofit, the average indoor temperature will rise to that of post-1980 buildings, i.e. to 22°C. We hereby aim to avoid overestimating the energy saving potential resulting from retrofit. To account for the regional climate we use gridded daily mean temperature and daily global horizontal irradiance data for the base year (2015), with a high resolution of 1 km by 1 km. The top-down approach presented by Berger and Worlitschek\(^13\) is combined with the SwissRes model\(^3\). This allows us to calculate individual thermal energy demand for each building. A GIS-based algorithm allows then the aggregation of the individual techno-economic potential for each climate pixel and the representation of the data in form of a gridded map.

2.2. Cost-effectiveness of retrofit package
The analysis of the cost-effectiveness of the retrofit package is based on the Energy Efficiency Cost Curve (EECC) approach representing the specific cost of energy savings\(^14\). We adapt the levelized cost approach described in our previous study on the techno-economic potential of single element retrofit measures\(^4\), with adjustments to allow the estimation of the potential of retrofit packages instead of single elements. In this study, we consider a common time horizon (\(t_h\)) for all building elements of 30 years, which is covering the shortest lifetime of all the building elements (windows). Previous analysis considered only the full cost of the retrofit measures. However, several scholars argue that in the case of older buildings this is not reasonable because they anyway require renovation to maintain the quality

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\(^1\) 9 (# of construction periods) * 2 (# of building types) * 3 (# of rural/urban typologies) * 26 (# of cantons) * 6 (# of heating systems) = 8424 (# of archetypes). More details on the selection criteria of the archetype categories can be found in\(^2\)

\(^2\) The Energy Performance Gap (EPG) is defined as the difference between the actual consumption of the building compared to the results of our simulation. In general, older buildings consume less and newer buildings consume more in reality compared to the simulated demand\(^7,8\).
and liveability of the building. Instead, only the cost related to energy efficiency improvement should be taken into account when considering the cost-effectiveness of the efficiency improvement [14]. This improvement cost is calculated using cost regression functions for building elements derived from a study from Germany on billed costs for over 1000 individual retrofit projects [15]. The Euro prices of 2015 are converted to the Swiss context with the average annual exchange rate to Swiss Franc of 1.07 for this year [16] and with a surcharge of 60% according to a market survey of international construction prices [17]. Furthermore, the investment costs are given as fixed costs ($I_{fixed}$) per square meter element and additional costs ($I_{thickness}$) per square meter element depending on the thickness of the additional insulation material assuming an average thermal conductivity ($\lambda$) of 0.035 W/(m·K) (see Table 1). For windows, we assume that the entire window will be replaced.

A retrofit is assumed if for a given archetype and element, the current U-Value is higher than the required U-Value (see Table 1). The related thickness of the additional insulation ($t$) is calculated using equation (1).

$$t = \frac{\lambda}{U_{insulation}} = \lambda \cdot \left( \frac{1}{U_{required}} + \frac{1}{U_{current}} \right)$$

We introduce the constraint that the thickness of the additional insulation is at least 3cm to prevent very uneconomic measures. Using the data presented in Table 1, the investment cost for each building element ($el$) can be calculated thereby accounting for the respective surface ($A$) per archetype as shown in equation (2).

$$I_{envelope} = \sum_{el=1}^{A} \left( (t_{el} \cdot I_{thickness,el} + I_{fixed,el}) \cdot A_{el} \right)$$

We are using equation (2) first for calculating the full costs and next for the improvement costs. We assume a social discount rate of 3% ($f_{DR}$). Following the approach of our previous study [4], the specific or levelized costs (LCOE) are derived from the annualized net present value ($NPV$) of the full retrofit package divided by the respective annual savings of final energy ($\Delta E$) as shown in equation (3) (final energy is defined as the total of fuel energy and electricity). The NPV is the discounted annual cashflow of all the investment and operation costs minus the avoided costs from energy savings.

$$LCOE = \left( \frac{-NPV \cdot f_{DR}}{1 - (1 + f_{DR})^{-T_N}} \cdot \frac{1}{\Delta E} \right)$$

3. Results

The simulation of the space heating demand with the mentioned adjustments to EPG and the climate data of 2015 results in an estimated final energy demand of 45 TWh/a for the Swiss residential building stock, comprising roughly 1.6 million buildings.

| Measure by building element | Gr-In | Wa-Ex | Ro-Ex | Wi-Ne | Wi-Ne |
|-----------------------------|-------|-------|-------|-------|-------|
| Building element            | Ground | Wall | Roof | Window | Window |
| Retrofit measure            | Interior insulation | Exterior insulation | Exterior insulation | SFH & MFH | SFH & MFH |
| Building type               | SFH & MFH | SFH & MFH | SFH & MFH | SFH | MFH |
| U-Value required [W/(m²K)]  | 0.24 | 0.19 | 0.18 | 1 | 1 |
| Full cost fixed [CHF/m² element] | 93 | 34 | 19 | 91 | 86 |
| Full cost add. [CHF/cm insulation] | 3 | 5 | 4 | 0 | 0 |
| Improvement cost fixed [CHF/m² element] | 93 | 34 | 19 | 91 | 86 |
| Improvement cost add. [CHF/cm insulation] | 3 | 5 | 4 | 0 | 0 |
3.1. Energy savings
In total, the simulation with SwissRes reveals that 25.8 TWh/a of final energy (57%) could be saved by applying the full envelope retrofit to the residential building stock. Figure 1 shows the resulting potential spatial energy savings.

As could be expected, the highest total energy savings can be achieved in urban centres of Switzerland. However, specific energy savings are highest in rural mountainous areas (north-west, south and south-east), due to older buildings and colder climate conditions [6,13]. A retrofit of individual buildings would therefore be most effective here. However, if larger amounts of energy savings are envisaged, district-wide retrofits in areas with high density would naturally be more effective.

3.2. Cost effectiveness analysis
According to our cost-effectiveness analysis the total investment cost for retrofitting the entire Swiss residential building stock would amount to roughly 247 billion CHF, which equals to approximately 590 CHF per m² of ERA. For the improvement cost, the total investment costs reduces to 52 billion CHF and 125 CHF per m². The Energy Efficiency Cost Curve (EECC) in Figure 2 indicates that for full costs, only a very small percentage of the energy savings is cost-effective.

In contrast, if only the investment costs related to the thermal improvement are considered (i.e., improvement costs), it becomes economically attractive to retrofit almost the entire building stock.
**Figure 2** indicates that a deep envelope retrofit of the residential building stock is not cost-effective for most of the buildings when considering the full costs. The spatial distribution of both full costs and improvement costs per spatial unit (1 km²) are visualized in **Figure 3**. Again, it is obvious that there are only a very limited number of regions where cost savings could be expected when considering full costs. Even though not cost-effective, the lowest specific costs occur mainly in the rural mountainous regions. The regions identified as having a high cost-effectiveness in **Figure 3** seem to largely coincide with the regions with a high specific energy saving potential of **Figure 1**.

![Figure 3 Specific cost of energy savings for full and improvement costs by 1km² resolution.](image)

### 4. Discussion

While the results of the SwissRes model confirm a high energy saving potential (57%) of a deep envelope retrofit, the overall saving potential is reduced from 43 TWh/a to 25.8 TWh/a compared to our previous study [4]. This reduction is related to the EPG correction, which reduces the risk of overestimating the energy saving potential for retrofits [10,11]. However, this study showed that there is a significant increase in cost-effectiveness when considering improvement costs instead of the full costs of the retrofit. This is line with the findings of Amstalden et al. [18], who found that deep energy retrofit of building envelopes in Switzerland is economically viable only under very favourable conditions. Our findings hence confirm the recommendations of the European Commission arguing for energy retrofitting in line with the buildings’ natural renewal cycle [19]. It should be noted that the two cost approaches presented here are extreme cases, where either all costs are assigned to the energy retrofit (full cost approach) or only costs that are strictly related to energy efficiency improvement are counted (improvement cost approach) while all other costs are disregarded even if they (partly) occur. Moreover, it should be considered that the different building elements (wall, roof, ground, and window) have different lifetimes [19]. Future studies should therefore include different cost approaches, in which the residual value of buildings before and after retrofit is taken into account, as well as the cost of renewing a building element at the end of its lifetime [20]. The historic centres of Zurich, Bern and Geneva are locations where the absolute energy saving potential is high (Total energy savings according to Figure 1) and energy retrofit is economically viable according to the improvement cost (**Figure 3**). However, the real potential can be expected to be lower because these city centres are often comprise listed buildings which must not be retrofitted with an exterior insulation. The approach could be refined by isolating these cases and applying a more expensive and less effective interior insulation retrofit package. Additionally, it should be considered that future climate will change and consequently also the overall energy demand for space heating. Furthermore, uncertainties related to the model parameters as presented in our previous study could increase or decrease the energy demand by up to 45% [3]. This would have an influence on the energy savings and subsequently the cost-effectiveness.
5. Conclusion

Our analysis confirms the existence of a high energy saving potential related to deep envelope retrofit for the Swiss residential building stock, with 57% reduction of final energy even after correcting for the EPG. However, when considering the full investment costs of the retrofit, less than 1% of these savings are cost-effective. If a building anyway needs to be renewed and therefore only the improvement cost are considered, basically the entire energy saving potential is economically viable. The results of the spatial analysis show that rural regions in mountainous areas feature the highest specific energy saving and cost-effectiveness potential, due to the older building stock and colder climatic conditions. Yet, for the improvement cost approach also the historic centres of Zurich, Bern and Geneva show favourable economic conditions for retrofitting. The location and distribution of the identified hot spots of this study can offer valuable information for policy makers or energy utility companies which are envisaging the implementation of large-scale deep energy retrofit measures. Moreover, the spatial resolution for energy retrofit potential could support the development of scenarios or roadmaps for a large-scale energy retrofit of the Swiss residential building stock.

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