Cost-optimal retrofit analysis for residential buildings

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Abstract. The current retrofit rate in Switzerland is very low. Among other reasons this is attributed to a lack of knowledge about cost-optimal retrofit strategies. In this work we carry out a holistic cost-optimal retrofit analysis for a Swiss single-family house. First, currently popular retrofit measures including all incurring lifecycle costs are identified and collected. Thereby, building systems as well as building envelope retrofit measures are considered. The retrofit measures are then combined to form a wide range of applicable retrofit strategies which are assessed in terms of cost-effectiveness and environmental impact. The calculation methodology considers the impact of building envelope retrofit measures on the design and efficiency of the heating system. For the case study building, the most cost-optimal retrofit strategy is to combine a geothermal heat pump with inter-rafter roof insulation and cellar ceiling insulation. The results indicate that the choice of heating system is much more crucial in terms of cost-effectiveness than building envelope measures. With respect to reducing primary energy consumption, building envelope measures are indispensable, however, when aiming for reducing greenhouse gas emissions, the choice of heating system becomes dominant.

1. Introduction
Switzerland must drastically reduce final energy consumption and greenhouse gas (GHG) emissions in order to achieve the goals of the Energy Strategy 2050 and meet its commitment to the Paris Agreement. The Swiss building sector accounts for 44% of final energy consumption and for 27% of GHG emissions and therefore offers great reduction potential [1,2]. Because of the slow turnover of building stock, widespread retrofitting of existing buildings is needed. However, the current retrofit rate in Switzerland is very low. Only about 1% of the 1.8 million Swiss buildings are retrofitted annually for energy efficiency [3].

Among other reasons this is attributed to a lack of knowledge about cost-optimal retrofit strategies. Homeowners are overwhelmed with the wide range of possible retrofit measures and often simply rely on the advice of local craftsmen [4]. Even if energy consulting services are obtained, often, not all feasible retrofit measures nor the interrelations of combined measures are considered. This may lead to the fact that the cost-optimal retrofit strategy is missed.

With this view, a holistic cost-optimal retrofit analysis for a Swiss single-family house is carried out as a case study. For this purpose, retrofit measures for single-family houses that are in line with current practice are identified and collected including all incurring investment costs. The retrofit measures are combined to form retrofit strategies which are then assessed in terms of cost-effectiveness and environmental impact. Finally, the cost-optimal retrofit strategy is determined and discussed.
2. Methodology

2.1. Selection of retrofit measures

The following three types of retrofit measures are considered: Heating systems (HS) based on renewable energy sources that are used for space heating and domestic hot water (DHW), DHW systems based on renewable energy sources that are used for DHW only and building envelope (BE) measures that reduce the demand for space heating by improving the building envelope.

In 2017, old heating systems that are replaced by new heating systems based on renewable energy sources are mainly replaced by heat pumps (73 %), wood-fired heating systems (22 %) and district heating connections (5 %) [5]. Among the heat pumps, brine-to-water heat pumps with geothermal probes (geothermal heat pumps) and air-to-water heat pumps are mainly installed in single-family houses according to interviews with heating planners and installers. In terms of wood-fired heating systems, pellet boilers are most popular [6]. Therefore, geothermal heat pumps, air-to-water heat pumps (inside and outside installation), district heating as well as pellet boilers are selected as heating systems for the retrofit catalogue.

In terms of DHW systems, mainly thermal solar collectors and heat pump boilers are supported with subsidies in Switzerland [7–9]. Consequently, the share of thermal solar collectors and heat pump boilers for DHW rose by over 70 % between 2011 and 2016 [1]. These two trending DHW systems are therefore selected for the retrofit catalogue.

Considering retrofit measures on the building envelope, mainly the following components were retrofitted in 2017: the roof (49 %), façade (34 %), components against unheated space (9 %) and windows (6 %) [5]. To identify the specific retrofit measures, a building physicist was interviewed. In case of (pitched) roof retrofits, either inter-rafter insulation or a complete roof renovation is usually applied. For façade retrofits, an external thermal insulation composite system (ETICS) is most often applied. Otherwise a ventilated curtain façade is installed. The following three insulation materials are usually used in façade retrofits: mineral wool, expanded polystyrene (EPS) and rigid foams like polyisocyanurate (PIR) or polyurethane (PUR). Among the insulation of components against unheated space the cellar ceiling insulation is popular and in case of windows replacement, windows with triple-glazed insulating glass are predominantly installed. Therefore, retrofit measures for the roof, façade, cellar ceiling and windows with different insulation materials (mineral wool, EPS and PIR/PUR) and different insulation thicknesses are selected for the retrofit catalogue.

2.2. Heating demand

The demand for space heating is determined for the reference case (no retrofit measures) as well as for each retrofit strategy using a monthly quasi-steady-state calculation from the Swiss standard SIA 380/1. The simulation tool Lesosai is used for this purpose. However, the pre-set SIA 380/1 standard values for room temperature, occupancy and electricity demand are replaced by measured values in order to increase the accuracy. The measured values were obtained in winter 2016/2017 using a wireless sensor network in the reference building. The heat demand for DHW is also calculated with the SIA 380/1 standard and assumed to remain constant for each retrofit strategy.

2.3. Impacts of improved building envelope on heating system

In order to perform a holistic and accurate retrofit analysis that outputs the cost-optimal retrofit strategy, it is crucial to consider the positive impacts of building envelope retrofit measures on the efficiency and design size of the heating system.

If the insulation of the building envelope is improved, the supply temperature of the heating system can be reduced. This impacts the efficiency of the heat pump operation, i.e., the coefficient of performance (COP) increases. In order to calculate the impact of building envelope retrofit measures on the supply temperature, the steady-state model developed by [4] is used. Thereby, the overall improvement of the building envelope U-value for each retrofit strategy together with measured supply and return temperatures, measured room temperatures as well as external temperatures are used to
calculate a new heating curve (supply temperature as a function of the external temperature) for each retrofit strategy.

In addition to lowering the supply temperature, building envelope retrofit measures also lower the heating load. Therefore, the heating load is recalculated for each retrofit strategy according to the Swiss standard SIA 384.201. Since the heating systems are designed so that their maximum heating power matches the heating load, the heating system can be down-sized if the heating load is sufficiently reduced by building envelope retrofit measures. This leads to lower investment costs for the heating system.

2.4. Final energy demand
In this retrofit analysis, only the final energy demand for space heating and DHW is considered. Since the electricity demand for lighting and electrical appliances is not impacted by the retrofit strategies, it is excluded from the analysis. Moreover, neither cooling nor mechanical ventilation is taken into account.

For the oil boiler (reference case), pellet boiler and district heating, the final energy demand (in kWh/a) is calculated with the efficiencies given in the Swiss standard SIA 380/1. For heat pumps, however, no fixed efficiency is assumed since their COP values depend very much on the heat source temperature (cold reservoir) and supply temperature (hot reservoir). Since the supply temperatures change depending on the retrofit strategy, the efficiencies of the heat pumps are recalculated for each retrofit strategy. Therefore, the seasonal coefficient of performance (SCOP) is calculated with a numerical model similar to the one developed by [10], which employs the bin-method: For every hour, the COP is recalculated using the current source temperature and supply temperature. In order to calculate the seasonal performance factor (SPF) of the heat pump system, the electricity consumption of circulation pumps (charging and source pumps) and due to legionella protection of DHW, the thermal storage losses and the energy losses due to the on-off cycles are also taken into account according to the Swiss standard SIA 384/3 and [11]. The final energy demand is then calculated by dividing the heat demand for space heating and DHW by the SPF.

2.5. Energy prices and environmental factors
The energy prices, primary energy factors and GHG emissions factors used in this retrofit analysis are indicated in Table 1 [12–14]. The information relates specifically to Switzerland.

| Energy carrier                  | Energy price [CHF/kWh] | Primary energy factor [kWh/kWh] | GHG emission factor [kg CO₂eq/kWh] |
|--------------------------------|------------------------|--------------------------------|-----------------------------------|
| Oil                            | 0.10                   | 1.24                           | 0.3024                            |
| Wood pellets                   | 0.08                   | 1.20                           | 0.0288                            |
| District heating (Swiss average)| 0.09                   | 0.87                           | 0.1080                            |
| Electricity (Swiss consumer mix)| 0.21                   | 3.00                           | 0.1008                            |

2.6. Lifecycle costing
In order to calculate the lifecycle costs of the retrofit strategies, investment costs, operational and maintenance (O&M) costs, energy costs and value added taxes (VAT) are taken into account. The investment costs include all costs incurred by the homeowner, including planning costs, costs for permission procedures and disposal costs of replaced components, and were determined on the basis of quotations from local manufacturers, craftsmen and installers. Subsidies are not taken into account since they vary from canton to canton and might change over time. Co-benefits of retrofit measures, such as higher thermal comfort, are also not taken into account. The O&M costs represent the average Swiss O&M costs depending on the heating system type according to the Swiss building technology association ‘suissetec’. The energy costs are calculated with the final energy demand and the energy prices indicated in Table 1. The lifecycle costs are calculated using the annuity method, which is the economic evaluation system of the Swiss Federal Office of Energy (SFOE) [15]. Under the annuity method, all costs incurred are converted into constant annual payments (annuities). The economic
lifetimes are specific to the individual components of the retrofit measures and correspond to the Swiss standard SIA 480. According to the current market situation, a real interest rate of 0% is chosen [16]. A retrofit strategy is cost-effective if its lifecycle costs are lower than in the reference case [12]. The most cost-effective retrofit measure, i.e. the one with the lowest lifecycle costs, is described as cost-optimal.

3. Retrofit catalogue
Table 2 shows the currently popular retrofit measures for a Swiss single-family house including the specific investment costs. The cost data was obtained from quotations of local installers and planners.

| Code  | Retrofit measure (U-values in W/(m²*K)) | Costs |
|-------|----------------------------------------|-------|
| RC    | Oil boiler                             | 16310 CHF + 133 CHF/kW |
| RC    | Washing and repainting façade          | 26 CHF/m² | 
| RC    | Grinding, putting and painting the underside of the roof | 9 CHF/m² | 
| RC    | Scaffolding                            | 38 CHF/m² | 
| RC    | Repainting of windows                  | 83 CHF/m² | 
| HS_1  | Brine-to-water heat pump with geothermal probes | 28'500 CHF + 2'122 CHF/kW |
| HS_2  | Air-to-water heat pump (outdoor installation) | 35'360 CHF + 648 CHF/kW |
| HS_3  | Air-to-water heat pump (indoor installation) | 44'560 CHF + 716 CHF/kW |
| HS_4  | District heating                        | 36'920 CHF + 128 CHF/kW |
| HS_5  | Pellet boiler                           | 74'380 CHF + 97 CHF/kW |
| DHW_1 | Thermal solar collectors                | 3'842 CHF/occupant |
| DHW_2 | Heat pump boiler                        | 1'747 CHF/occupant |
| BE_1a-b | Inter-rafter roof insulation with mineral wool (a: 0.26, b: 0.18) | 70; 79 CHF/m² | 
| BE_1c-d | Inter-rafter roof insulation with premium mineral wool (c: 0.21, d: 0.15) | 84; 95 CHF/m² | 
| BE_2  | Complete roof renovation with inter- and over-rafter insulation (0.04) | 407 CHF/m² | 
| BE_3a-c | ETICS with mineral wool (a: 0.21, b: 0.17, c: 0.13) | 320; 342; 363 CHF/m² | 
| BE_3d-f | ETICS with EPS (d: 0.19, e: 0.16, f: 0.12) | 274; 286; 317 CHF/m² | 
| BE_3g-i | ETICS with PIR (g: 0.14, h: 0.12, i: 0.09) | 351; 391; 466 CHF/m² | 
| BE_4a-c | Ventilated curtain façade with EPS (a: 0.19, b: 0.16, c: 0.12) | 353; 384; 415 CHF/m² | 
| BE_4d-f | Ventilated curtain façade with mineral wool (d: 0.21, e: 0.17, f: 0.13) | 384; 415; 446 CHF/m² | 
| BE_5a-b | Cellar ceiling insulation with mineral wool (a: 0.39, b: 0.19) | 80; 112 CHF/m² | 
| BE_6a-b | New windows with triple-glazed insulating glass (a: 0.83, b: 0.76) | 679; 690 CHF/m² | 

4. Case study

4.1. Reference building
The reference building is a single-family house with four occupants in St. Gallen, Switzerland, which was built in 1973. The dwelling has three floors with double layer brick walls and a energy reference area (ERA) of 238 m². The climate is temperate. An oil boiler is used both for space heating and DHW. For heat dissipation a floor heating system with a design supply temperature of 45 °C is used. Without any retrofit measures, i.e., in the reference case (RC), the building has a heat demand for space heating of 54'510 kWh/a and a heat demand for DHW of 3'820 kWh/a.

4.2. Cost-optimality
In order to reduce the number of building envelope retrofit measures, the cost-optimal retrofit measure for each building envelope component (i.e., roof, façade, cellar ceiling and windows) is determined in a first step. The four cost-optimal building envelope measures BE_1b, BE_4a, BE_5b, BE_6b are then used together with the heating systems and DHW systems to form all possible combinations of retrofit measures, whereby each combination corresponds to a retrofit strategy. If a building envelope component is not affected by a retrofit measure, the maintenance measure from the reference case (RC) is applied. Furthermore, the two DHW systems are combined with an oil boiler which is used for space heating. Table 3 shows the lifecycle costs of all retrofit strategies in the form of annuities.
Although the geothermal heat pump causes high investment costs, the low O&M and energy costs as well as the long lifetime of the geothermal probes lead to low lifecycle costs. The inter-rafters roof insulation with 20 cm mineral wool and cellar ceiling insulation with 16 cm mineral wool (HS_1 and BE_1b_5b). The result is relatively stable in various sensitivity analyses regarding energy prices and interest rates. Although the geothermal heat pump causes high investment costs, the low O&M and energy costs as well as the long lifetime of the geothermal probes lead to low lifecycle costs. The inter-rafters roof insulation as well as the cellar ceiling insulation have relatively low investment costs and still lead to a considerable reduction in heating demand.

4.3. Environmental impact

The impacts of the retrofit strategies on primary energy consumption (PEC) and GHG emissions are shown in Figure 1 and Figure 2. For each space heating and DHW system, the following two retrofit strategies are shown: No building envelope retrofit measures (blue points) and all four building envelope measures (red points).

![Figure 1](image1.png)

![Figure 2](image2.png)

**Figure 1.** Impact of retrofit strategies on lifecycle costs and primary energy consumption

**Figure 2.** Impact of retrofit strategies on lifecycle costs and GHG emissions

5. Discussion and conclusion

5.1. Cost-optimality

For the analyzed reference building, the cost-optimal retrofit strategy is to combine a geothermal heat pump with inter-rafters roof insulation with 20 cm mineral wool and cellar ceiling insulation with 16 cm mineral wool (HS_1 and BE_1b_5b). The result is relatively stable in various sensitivity analyses regarding energy prices and interest rates. Although the geothermal heat pump causes high investment costs, the low O&M and energy costs as well as the long lifetime of the geothermal probes lead to low lifecycle costs. The inter-rafters roof insulation as well as the cellar ceiling insulation have relatively low investment costs and still lead to a considerable reduction in heating demand.
Table 3 further shows that the choice of heating system is much more crucial in terms of cost-effectiveness than building envelope measures. Whether a retrofit strategy is cost-effective depends primarily on which heating system it includes. Among the heating systems, only the heat pumps (HS_1, HS_2 and HS_3) are cost-effective, i.e., only retrofit strategies that include a heat pump outperform the oil boiler financially, regardless of what building envelope retrofit measures are taken.

However, these findings refer explicitly to the reference building where the heat pumps are favored due to the lower supply temperature (for an old building). If the reference building required a higher supply temperature, building envelope measures could become crucial in terms of cost-effectiveness.

5.2. Environmental impact

Figure 1 shows that PEC is influenced by both retrofit measures on the building envelope and the choice of heating system. Switching from the oil boiler (RC) to the geothermal heat pump (HS_1) or district heating (HS_4), already leads to a great reduction in PEC. However, if a really low consumption level should be achieved, retrofit measures on the building envelope are indispensable. Therefore, the retrofit of all four building envelope components leads to very low PEC, irrespective of the heating system. However, it is questionable to what extent PEC is a suitable indicator of environmental impact, since no distinction between renewable and non-renewable primary energy is made.

In contrast to PEC, GHG emissions are highly dominated by the choice of heating system as shown in Figure 2.Switching from an oil-based heating system (RC, DHW_1 and DHW_2) to a heating system based on renewable energy sources leads to enormous savings in GHG emissions, even if no retrofit measures on the building envelope are taken. For this reason, retrofit measures on the building envelope are only efficient in reducing GHG emissions when the heating system is oil-based. In case the reduction of GHG emissions is the main goal, the focus should be on switching to a heating system based on renewable energy sources.

Finally, it has to be highlighted that embodied energy and embedded GHG emissions are not taken into account in this study. Even if embodied energy and embedded GHG emissions play a subordinate role in retrofitting compared to the new construction, the results could be slightly different.

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