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Balancing envelope and heating system parameters for zero emissions retrofit using building sensor data

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HIGHLIGHTS

- A steady-state model to illustrate retrofit measures on the supply temperature of the heating system is proposed.
- Low supply temperatures allow for emission free heating of the building.
- Model applied to an existing retrofit scenario of a listed building.
- Sensor network to determine the model parameters is developed and installed.
- Listed building is suitable for low temperature heating system.

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ABSTRACT

Retrofit measures are an effective means to improve both the heating energy and carbon footprint of a building. On one hand, reducing the losses through the envelope reduces the energy consumption. On the other hand, updating the heating from a fossil-fuel based system to an emission-free one bears the potential for CO_2-emission free operation. The latter can be achieved if the supply temperature of the heating system can be sufficiently reduced, such that the operation of a heat pump with a high coefficient of performance becomes feasible. For this, typically the heating area is increased to facilitate the heat transfer. Qualitatively, it is understood that increasing the heating area and improving the insulation of the envelope allows one to lower the supply temperature. However, it is unclear how these improvements relate to each other, or what their individual or combined effect is. In this research, we present a steady-state model to illustrate the impact of retrofit measures on the supply temperature. The model requires the determination of two dimensionless parameters, as well as an estimate for the thermal transmittance (*U*-value) of the envelope. For this, we developed a flexible, low-cost sensor network. We apply our model to a real retrofit scenario of a historically listed building in Zurich, Switzerland, and show that the current state of the building is already suitable for a low temperature heating system. The findings of our model are confirmed by a calibrated dynamic building simulation. The proposed model provides a means to relate energy savings to reduction of green house gases, and, thus to reduce the CO_2 footprint of the building stock.

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1. Introduction

Worldwide, buildings consume up to 30% of the primary energy and are responsible for over 30% of the anthropogenic green house gas (GHG) emissions. Buildings also hold the greatest potential for energy savings [1]. In Switzerland, the existing building stock accounts for 45% of the primary energy consumption, the residential buildings alone contribute 27% [2]. Retrofitting measures are an efficient means to reduce energy consumption and improve the energy efficiency of buildings. Considering that in Switzerland the retrofitting rate is only about 1–2%, it is clear that there is a huge potential to increase the energy performance of the whole building stock, thereby reducing its CO_2 emissions considerably [3,4]. A similar situation can be observed Europe-wide [5].

Studies show that this low retrofit rate is partly due to the difficult nature of making a decision in a complex environment. Optimal retrofits differ in, e.g., context of the site, function, occupancy, the envelope, and systems. Therefore deciding on the appropriate retrofit is challenging. About 70% of the residential building stock in Switzerland is owned by private homeowners or private cooperatives [2]. Many of the homeowners are

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overwhelmed when facing the retrofit of their building. They rely on the advice of craftsmen known to them, who usually recommend a single measure from their domain of knowledge rather than a complete set of measures. To empower owners for better decision-making and, thus, to raise the retrofit rate, it would be favorable to provide more and better information on the energetic behavior of the specific building. This could then allow for tailoring efficient and custom retrofit measures for the individual building.

Key to the development of optimal retrofit measures is the assessment of the current performance of the building in question, in particular its heating demand. For this, the Swiss code SIA 380/1 a heating energy calculation to be performed based on estimated values for the envelope, the systems and standardized inputs for loads and occupancy [6,7]. This *expert* approach is a generalized means of assessing a building, yielding good results when averaged over a large number of buildings. On the other hand, the calculations use simplifications and empirical figures and weighting factors, grouping buildings by a certain building type, which may neglect the individual characteristics and environment. Retrofit proposals, including future performance predictions, are then made based on these first estimates. However, neither the accuracy of the initial estimates nor the efficiency of the derived predictions is ever validated experimentally. In fact, a recent study on 3400 German homes concluded that the actual heating energy was 30% less than computed by the code [8]. This discrepancy between calculated performance and actual energy consumption, the *prebound effect*, has also been observed in the Netherlands, Belgium, France and in the UK [8]. There is no conclusive study on this topic in Switzerland yet. However, in this research we will find some indication for the existence of the prebound effect. We argue that care must be taken when considering retrofit scenarios based on unverified initial estimates on the building behavior.

As an energetic goal for retrofit measures, the (Net) Zero Energy Building concept is recently gaining increasing interest. In fact, several countries are adopting it as their future target for optimal building design in order to mitigate CO_2 emissions [9]. While a multitude of definitions and calculation metrics exists [10], for our research it is sufficient to apply the most general concept that a retrofit scenario must not only consist of reducing the energy consumption, i.e., the demand side, but also consider updating the supply side to a low emission, or emission-free, system. Only a combination of both sides can provide the necessary impact to reduce CO_2 emissions significantly, and thereby reduce the impact of buildings on global warming. These considerations put additional complexity on planing retrofit measures.

In cold and dry climates such as in Switzerland, heating represents roughly 60% of the total energy consumption of the building. Therefore, in this research we consider heating demand and supply. Typical retrofit measures to reduce the heating demand include applying insulating layers on the walls and/or exchanging windows. One the demand side, the typical measure is to update a dated burner to a new one with a higher burning efficiency, which reduces the fuel consumption. Little attention is given as to how the improvements on the envelope can change the settings of the heating system.

Recently, a series of case studies have investigated combinations of retrofit measures consisting of heat pump and envelope insulations for a single-family home in the Zurich, Switzerland climate [11]. The focus of these studies was the reduction of global warming potentials (GWP) as well as the aesthetic impact of the measures on the architecture of the building. For this, numerical simulations (TRNSYS) were employed to determine the theoretical overall heating demand as well as the embodied and operational GWP. It was found that once a fossil fuel based heating system is replaced by an electrical heat pump, the current regulation of requiring highest possible insulation on the envelope may be counterproductive in terms of GHG emissions [12]. The influence on the flowrates and supply temperatures for the heating system itself were not investigated.

However, this is an area where we hypothesize a large potential for improvements, as an increase of insulation reduces the heating demand, which in turn can reduce flowrates and/or supply temperatures. Reducing the supply temperature makes low temperature heating supply systems interesting and economically viable. Our objective is to achieve low supply temperatures in order to be able to change the heat generation system from conventional, fossil-fuel based one to a heat pump with a high coefficient of performance (COP), given by

$$\mathrm{COP} := g\frac{T_S}{T_S - T_{\mathrm{source}}}, \tag{1}$$

where g is the efficiency of the heat pump, T_S is the required supply temperature, and T_{source} the temperature of the source, e.g., geothermal (see [13] for a recent review of current heat pump systems). Increasing the COP by decreasing T_S reduces the amount of electricity required to operate the heat pump. If this remaining necessary electric energy can be then obtained from a renewable energy source, e.g., photovoltaics, then the heating system of the building can be operated CO_2 free. Hence the importance of obtaining a low supply temperature and taking a holistic approach when considering possible retrofit measures.

Therefore, in this work, we propose that the typical retrofit question should not be *How can heat losses through the envelope be minimized?*, but rather *What measures are necessary to switch to a lower supply temperature and, thus, to an emission-free supply system?*. It is possible to employ building performance simulation tools to provide an answer [14,15]. However, these tools are more suitable in the early stages of a design rather then in a retrofit scenario, due to the large number of uncertainties required to calibrate the model. For a simplified investigation of relationships, in Section 2 we develop an analytical steady-state model that relates improvements on the envelope, specifically the thickness and material of the insulation to the parameter of the heat supply, i.e., the heating area. We show their combined effect on the supply temperature in one zone. The model requires the determination of two dimensionless parameters from simple temperature measurements, as well as inferring the current U-value of the envelope using a parameter estimation method. For this we developed a low-cost sensor network using off-the-shelf components based on the Arduino platform, which is described in Section 3.

We use a real retrofit scenario on a listed five-storey building in the centre of Zurich, Switzerland, as a case study, and demonstrate two main results. First, in Section 4 we verify that the heating consumption is indeed greatly overestimated by current code-based techniques. Second, in Section 5, we apply our model to the retrofit scenario and show that the current state of the house is already quite suitable for a low temperature heating system. We verify these findings and validate our model by an extensively calibrated dynamic building simulation model in Section 6. After a discussion in Section 7, we conclude in Section 8 that our research contributes to transforming the current building stock into an emission free operation state by providing a quantification method for the potential of the reduction of the CO_2 footprint of a building.

2. Theory

2.1. Annual heating demand

The concept of heating degree-days can be used to estimate the annual heating demand Q_h indirectly through thermal losses as

$$Q_h = K_{\mathrm{tot}}\mathrm{HDD}, \tag{2}$$

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