Electricity demand flexibility potential of optimal building retrofit solutions

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Abstract. Swiss buildings, the majority of which will last beyond 2050, are responsible for a large share of energy demand and greenhouse gas emissions. Hence, building retrofit is considered as one of the most promising approaches to reduce those shares. However, reducing the energy load should not be an end in itself. The continuous integration of intermittent power sources in the electricity grid imposes new challenges to the supply-demand problem that might directly affect the retrofit process and vice-versa. Therefore, this paper aims to develop a model to analyze the demand flexibility potential of optimal retrofit solutions. Co-simulation and a rolling horizon approach are used to derive upper and lower electricity consumption profiles given some temperature comfort bands. Within those electricity bands, the feasible area provides insights on the extent by which the electricity consumption can be shifted within the comfort constraints. The method is applied to a building archetype. Results show that when the comfort constraints are relaxed the feasible area increases, e.g., up to five times for the case of enhancing the roof insulation, while building retrofit influences the electricity bands. Such a method could enhance the retrofit process and address both the emissions’ and the supply-demand balancing problem.

1. Introduction
The Swiss Federal Office of the Environment recently announced that Switzerland missed the emissions targets for 2020. However, the decarbonization of the country by 2050 is still the declared target. This implies that stronger and more effective methods to decarbonize different sectors need to be employed. Two of the main pillars of the Swiss Energy Strategy are increasing the energy efficiency of buildings and facilitating the integration of renewable energy technologies [1]. Several similar energy-related targets have also been established in Europe with a strong focus on building retrofit [2] because buildings consume a lot of energy and emit large amounts of greenhouse gas (GHG) emissions. More specifically, in Switzerland, buildings account for 24% of total GHG emissions [3] and 40% of total energy consumption [4]. Part of this energy is electricity and thus buildings can play a key role in the supply-demand balancing problem as the electricity grid is facing great challenges due to the increased integration of renewable energy technologies [5]. Consequently, buildings’ energy load could be reduced with building retrofit and also exploited for energy demand management.

1.1. Building retrofit
Building retrofit is the process of modifying a building after it has been constructed and occupied in order to make it more energy efficient. Yet, identifying optimal retrofit solutions is a complex process due to various competing objectives. Advanced approaches use combined simulation and optimization models to derive optimal retrofit solutions [6,7], while others use machine learning models [8,9].
1.2. Demand flexibility potential
The increased integration of renewable energy technologies leads to a partial shift from supply- to demand-side management. Buildings’ energy load can play a key role in the provision of demand flexibility. In [10], demand flexibility is defined as “the ability of a building to manage its demand and generation according to local climate conditions, user needs and grid requirements”. While there are various flexible loads in a building, demand flexibility with respect to the actual building is usually reduced to the electricity loads caused by heating and cooling. Quantifying the demand flexibility of a building is a crucial step towards demand response. There are indirect and direct methods and metrics for such quantification. Indirect methods focus on quantifying the cost and CO2 savings under specific market conditions [11]. Direct methods use metrics such as power capacity to quantify the flexibility potential [12]. The selection of the method and metrics to use depends on the flexibility sources and the focus of the study. A comprehensive list can be found in [13] and [14], respectively.

1.3. Added value
Building retrofit might affect the demand flexibility potential and vice versa. There exist studies that focus either on building retrofit or demand flexibility quantification. Yet, to the best of our knowledge, there are no studies which aim to develop a framework to analyze the demand flexibility potential of optimal retrofit solutions. Nevertheless, some studies identified the influence of randomly selected building retrofit solutions on the demand flexibility potential. A summary of those studies can be found in [15]. Our work aims to provide a methodology on analyzing the demand flexibility potential of residential buildings given a set of feasible and optimal building retrofit solutions. A flexible electricity area is calculated to identify the influence of building retrofit measures. The proposed methodology is built upon an advanced combined building simulation and optimization retrofit models. It can be applied at the planning phase and can give an overview of both the energy savings and the ability to adjust the power consumption depending on the requirements of the grid. The developed methodology is illustrated for an example real residential building archetype in Switzerland.

2. Methodology
In this paper, a model to analyze the potential feasible area, within which electricity flexible scenarios can lie, built upon a building retrofit model, is developed. The process, illustrated in Figure 1, starts with a simulation and optimization model that is used to derive optimal retrofit solutions. For the electricity-based solutions, i.e., using a heat pump, the potential for electricity demand flexibility is analyzed.

2.1. Building retrofit model
The selected building retrofit model consists of a building simulation and an optimization module. CESAR-P is used to derive energy demand profiles under various building envelope interventions (BEIs). The optimization module is an energy hub model, formed as a mixed integer linear programming problem [9]. The output is a Pareto front, i.e. a set of optimal retrofit solutions, given two objectives, total costs and CO2 emissions. Each of these solutions is characterized by its objective value, the selection and sizing of the energy systems, the renewable energy technologies and storage, and the BEI.

2.2. Demand flexibility model
The first step towards analysing the electricity demand flexibility potential is the definition of an accurate building model. Towards that direction, a detailed EnergyPlus model was built. More specifically, the building simulation model used in the building retrofit model is enhanced to account for a more detailed representation of the heating system. In this work, the detailed system used is a ground source heat pump with floor heating. Moreover, the ground floor of the building is insulated to ensure a location the heat source, i.e., the floor heating, and to make sure that the heating is not wasted to the ground. The second step is the definition of the simulation time. In order to obtain results for an entire year and reduce the computational cost, we make use of typical days. These are derived with the k-medoids algorithm with the use of the outdoor dry-bulb temperature. The third step is the selection of
the comfort bands within which the indoor temperatures should lie. More details on the typical days and the comfort bands are given in Section 3.

![Diagram](image)

**Figure 1.** Analysing the potential for demand flexibility on electricity-based optimal retrofit solutions

Inspired by [16], a co-simulation with a rolling horizon approach is used to calculate upper and lower electricity consumption bands. The area within these bands is the feasible area within which the electricity consumption can be shifted without violating the comfort constraints. Eventually, potential flexible scenarios’ cumulative electricity consumption are expected to lie within this area. Co-simulation is performed using the EnergyPlus co-simulation toolbox [17] and is intended to ensure that the inside air temperature is sustained within some comfort bands. Maximum and minimum consumption scenarios, for each of the derived typical days and the user specified comfort bands, are identified using the rolling horizon approach. The approach uses a horizon of 1.5 hours with a decision step resolution of 30 minutes. Half an hour is chosen as the resolution of the decision making as this is the minimum usual time that a heat pump should run without any change of state. The building model is used to predict the temperature over the decision horizon. However, it should be mentioned that the time resolution of the building simulation is 10 minutes. The simulation starts by predicting the inside temperature profile for the prediction horizon for all the possible combinations of on/off operation of the heat pump within the 90 minutes and with 30 minutes activation resolution, i.e., resulting in 8 combinations, with a time resolution of 10 minutes. The mean indoor temperatures for the prediction horizon are calculated and the activation sequence for the decision horizon is the one that leads to a maximum mean value for the maximum consumption scenario, and the one that leads to the minimum for the minimum consumption scenario. In the second iteration, we shift the prediction horizon by half an hour and we perform the same calculations. This process continues until the full simulation horizon is reached.

3. **Example building**

A single family house (SFH) archetype is selected to showcase the proposed methodology. This building archetype represents 660 Swiss SFHs [18]. It was built in 2003 and is heated by a gas boiler. It has one floor with a total area of 98.76 $m^2$. The comfort band selected, for which the feasible electricity area is computed, is set to 19.5 – 22.5°C for winter days based on SIA 180:2014 [19]. A winter day is considered a day with an average outside temperature over the past 48 hours, i.e. the day before and two days before, of less than 12°C. Moreover, a relaxed constraint comfort scenario is investigated, that is 19.0 – 23.0°C. The simulations were run for 5 winter days (Table 1), for which there is a need for heating, out of the 12 generated typical days for Neuchâtel weather conditions. In order to compare the feasible electricity areas of the different scenarios investigated we calculate the integral of the cumulative electricity consumption. This area is measured in k$Wh \cdot h$. 

![Diagram](image)
4. Results and discussion

4.1. Building retrofit optimization results

With the use of the building retrofit model we calculate ten Pareto front retrofit solutions for the example SFH. The necessary inputs in order to build the detailed building model are summarized in Table 2. For the retrofit solutions close to the cost-optimal, i.e., Pareto Front No. 1-6, the existing heating system is kept. CO₂ optimality is achieved by replacing the gas boiler with a heat pump. Since the building is relatively new and the construction materials already involve some insulation, the BEIs range from no enhancements to the enhancement of wall insulation and replacement of the windows with more efficient ones. It is worth mentioning at this point that the solutions that look identical, e.g., Pareto Front No. 3 and 5-6, differ in the selection and the sizing of the renewable energy technologies and storage installed.

### Table 2. Optimization results of the building retrofit model for the example building archetype.

| Pareto front No. | Energy system selection       | Energy system sizing [kW] | Building envelope intervention |
|------------------|-------------------------------|---------------------------|-------------------------------|
| 1-2              | Gas boiler (existing)         | 4.03                      | No                            |
| 3, 5-6           | Gas boiler (existing)         | 4.03                      | Wall & Window                 |
| 4                | Gas boiler (existing)         | 4.03                      | Window                        |
| 7                | Air source heat pump          | 4.03                      | No                            |
| 8                | Ground source heat pump       | 3.39                      | No                            |
| 9                | Ground source heat pump       | 2.84                      | Window                        |
| 10               | Ground source heat pump       | 2.47                      | Roof                          |

4.2. Potential for demand flexibility

The consumption bands are derived for Pareto Front points No. 8-10. In total, 30 bands are calculated for 5 typical days, 2 comfort scenarios and 3 BEIs. In Figure 2, the co-simulation results for typical day 2 are depicted for both comfort scenarios. The indoor temperature is kept within the comfort bands for the maximum (solid lines) and the minimum consumption (dotted lines) scenarios. There is an exception for the base comfort scenario in which the temperature, for all BEI scenarios, slightly exceeds the upper comfort limit for 20 minutes due to internal and solar gains. The jump in the inside temperature at 06:00 on the other hand is due to an increase in the internal gains due to occupancy, lighting and electric appliances. The temperature drop from 11:00 to 16:00 is due to natural ventilation.

Regarding the cumulative electricity consumption, the no BEI scenario leads to the maximum consumed electricity in both comfort scenarios. This is due to higher heat losses compared to the roof and window BEI scenario. For the base comfort scenario, we can observe a similar feasible area for both no and window BEI of 399 kWh ⋅ h and 385 kWh ⋅ h, respectively. This can be explained by the fact that there are very low solar gains and that the U-value and the g-value of the replaced windows are slightly lower than the existing ones. However, the roof BEI leads to a much smaller area of 92 kWh ⋅ h in this case. This is due to the fact that until 18:20 there is no flexibility potential, since the minimum and the maximum cumulative electricity profiles are equal to each other, and before 14:50 there is no need for heating. For the maximum consumption case, the heating system is off after midnight so as not to exceed the upper comfort limit in the morning, i.e., around 07:30. From 14:50 until 15:20 in both cases the heating system should be on and then turned off until 18:20 so as not to violate the temperature comfort levels. On the other hand, flexibility could be offered during the whole day in the no and window BEI. For the relaxed comfort scenario, there is no need for heating for the minimum consumption case. However, heating is activated in the maximum consumption scenario, leading to a flexibility potential
during the whole day for all BEI scenarios. The feasible area, within which the flexible profiles could lie, is lower when there is a BEI. The feasible area is $925 \text{ kWh} \cdot \text{h}$ for no BEI, $880 \text{ kWh} \cdot \text{h}$ for window BEI and $539 \text{ kWh} \cdot \text{h}$ for roof BEI. To sum up, relaxing the comfort constraints leads to both higher feasible areas and flexibility potential during the whole day for all BEI scenarios.

Figure 2. Feasible electricity consumption areas for typical day 2, i.e., 6th of November, for two comfort scenarios and three different building envelope interventions.

Typical day 4 is slightly colder but sunnier. It leads to flexibility potential during the whole day and higher feasible areas from 770 to 1025 $\text{kWh} \cdot \text{h}$ for the base comfort scenario and up to 1436 $\text{kWh} \cdot \text{h}$ for the relaxed comfort scenario. However, compared to typical day 2, the base case scenario, during ventilation time, leads to discomfort which could potentially be avoided by a larger temperature prediction horizon. Typical day 1 is the warmest day and for the base comfort scenario there is limited duration for which flexibility could be offered. For the no and window BEI, the flexibility potential starts from 18:20 while for the roof BEI from 19:30. For the coldest day, typical day 5, there is a constant need for heating for both minimum and maximum consumption for both comfort scenarios. This leads to smaller areas, from 529 to 1168 $\text{kWh} \cdot \text{h}$, compared to the warmer and sunnier typical day 4.

5. Conclusion
In this work, a model to analyze the potential for demand flexibility of residential buildings is provided for electricity-based optimal retrofit solutions. It can be used in the planning phase both to analyze the demand flexibility potential and as a performance indicator for a more informative building retrofit decision. The proposed method was applied to a SFH for two comfort scenarios. It could be observed that for this specific building envelope interventions, especially the enhancement of roof’s insulation, leads for most of the investigated scenarios to smaller feasible areas. Moreover, by relaxing the comfort constraints the feasibility area increases. In this study the potential for demand flexibility is investigated, however a direct quantification of the flexible power and how long can this be sustained would be necessary and is the focus of future work. Future research should also examine the integration of renewable energy technologies and storage at the building level since then more flexibility sources could
be investigated. Furthermore, the same approach could be applied to other electric heating systems, such as air source heat pumps and micro grid turbines and different weather files to reveal the influence of the heating systems and weather conditions on the demand flexibility potential. Finally, further investigations with a larger set of buildings are necessary in order to generalize the influence of building retrofit on the demand flexibility potential of residential buildings.

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