Retrofitting, district heating and energy storage: neighborhood energy planning

Diane von Gunten1, Jakob Rager1, Jérôme Kämpf 2,3, Fabien Kuchler4, Fabien Poumadère1

1Centre de Recherches Énergétiques et Municipales, Grand-Saint-Bernard 4, 1920 Martigny
2kaemco LLC, la Riaz 6, 1426 Corcelles-Concise
3Idiap Research Institute, Marconi 19, 1920 Martigny
4Elimes AG, Winkelgasse 2, 3900 Brig

E-mail: diane.vongunten@crem.ch

Abstract. We compare simulated energy retrofitting of individual buildings with energy refurbishments optimized at the scale of the neighborhood. For the neighborhood case, buildings can also be connected together through a heat network. We use a detailed three-dimensional model to estimate heating needs (CitySim) and a mixed-integer linear optimizer to analyze different options for energy refurbishment, including various heating technologies. According to our simulations, planning at the neighborhood scale results in slightly lower costs (about -5%) and lower CO2 emissions (about -60%) than planning energy refurbishment at the building scale, showing that integrated planning of energy refurbishment is beneficial from both environmental and economical points of view.

Keywords: refurbishment, optimization, CitySim, building

1. Introduction

About 35% of the final energy consumed in Switzerland is used for space heating and to produce hot water [1]. To reach the goals of the Swiss 2050 Energy Strategy [2], it is necessary to reduce this energy demand in residential buildings. Since a large choice of options is available to refurbish buildings and to improve heating systems, selecting the most adequate energy improvement for existing buildings is often complicated.

As a result, [3] and [4] have developed different optimization models to support the selection of retrofitting options and heating systems. However, these examples are centered on individual buildings and possible synergies between buildings of one neighborhood are neglected. When synergies between buildings are considered (e.g., [5], [6]), no comparison between energy refurbishment at the building scale and at the neighborhood scale is conducted. It is assumed that a larger scale would be beneficial, but a detailed analysis of this assumption is currently lacking.

Consequently, the OSCARS project aims to a) quantitatively compare options for refurbishment and equipment upgrade, b) investigate the impacts of planning these improvements at the multi-buildings scale, at which buildings can exchange heat. To this end, we focus on two case studies in the Swiss Alps. A detailed model of these two groups of buildings was prepared to estimate their heating and hot water needs under different insulation scenarios. Models of different energy conversion technologies for heating were also considered. Then, a
mixed-integer linear optimizer was used to find solutions with the lowest energy consumption together with the lowest simulated cost. To check our model results, the outputs from our optimization were compared with the refurbishment and heating equipment installed in one case study. Finally, the impacts of the scale and the creation of heat networks were analyzed in the refurbishment outcomes.

2. Short presentation of the case studies
The two neighborhoods studied are situated in the Swiss Alps in canton of Valais. The first case study (called village 1 in this paper) is used to compare our model with the optimization outputs. It is a REKA holiday village composed of nine buildings with seven residence buildings, one community building, and one reception house. It was constructed in 2014 in the village of Blatten-Belalp with the goal of minimizing its environmental impact, notably its CO\textsubscript{2} emissions and energy use. It is a (P+D) project from the Swiss Federal Office of Energy. The second case study (called village 2 in this paper) is a residential district called “Krommen Kelchbach” composed of 11 buildings in the village of Naters. Six of these buildings were constructed before 1990 with only two buildings refurbished after 1995. The five other buildings were constructed between 2005 and 2011. (Figure 1).

![Figure 1. View of the modeled buildings (village 2)](image)

3. Method
The simulation procedure [7] used here can be divided into three steps: 1) the preparation of a building-scale model to obtain the hourly heat loads of the buildings under different insulation scenarios; 2) the selection of typical days out of the 365 days simulated per scenario; 3) the optimization of the retrofitting and heating system.

3.1. Heat demand model
We model the hourly heat demand of the different buildings using CitySim [8], which is a software used to simulate energy flows in buildings. We develop three-dimensional models of the studied buildings and estimate their consumption based on the monitored weather data. The numerical model is then calibrated with the corresponding fuel consumption measurements (i.e., final energy) by refining the assumptions on its input parameters. We use weekly fuel consumption data for the village 1 and annual consumption data for the village 2. Difference between measured and modeled data is generally under 6%. The resulting calibrated model gives a stable base to compute the heating needs for the different insulation scenarios (see Table 1) that feed the optimization model.
3.2. Selection of typical days
To reduce computation time, we do not use the hourly heat demand for the whole year in the optimization model. Instead, we select seven typical days (using a clustering method from [9]) and the coldest day of the year. We then use the hourly demand from these selected days. The loss and gain for the seasonal storage and the different costs is then multiplied by the length of each cluster of typical days.

3.3. Optimization model
The optimization is performed using a mixed-integer linear programming solver called Gurobi [10]. The optimization objective is to minimize the total costs $C_{tot}$ (Eq. 1). Environmental goals are considered through additional constraints applied to the optimizer (Section 3.5).

$$C_{tot} = \sum_{tech} (CRF_{tech} C_{inv_{tech}} + C_{maint_{tech}}) + C_{oil_{purchase}} + C_{elec_{sale}} - C_{elec_{sale}}$$ (1)

where $CRF_{tech}$ is the capital recovery factor (Section 3.4), $C_{inv_{tech}}$ the investment costs by technology, $C_{maint_{tech}}$ the maintenance costs, $C_{oil}$ the annual costs of fuel oil, $C_{elec_{purchase}}$ the costs of electricity, and $C_{elec_{sale}}$ the gains linked to the electricity sale.

For each building, the optimizer can choose between 16 refurbishment strategies (Table 1) and seven technologies:

- Oil boilers for hot water and space heating.
- Daily storage of hot water used for space heating and daily storage for domestic hot water.
- Low-temperature heat pumps for space heating.
- High-temperature heat pumps for hot water.
- Combined heat and power plants (CHP).
- Photovoltaic (PV) panels. The electricity production is based on the CitySim results.
- Solar thermal panels. The heat production model is taken from [12] assuming an angle of 50° between the solar panel and the horizon.

Table 1. Description of the insulation (left) and windows (right) kits.

| Name | Wall [cm] | Roof [cm] | Descr.       | Name | Glazing   | Ug $[\frac{W}{m^2K}]$ | g [-] |
|------|-----------|-----------|--------------|------|------------|------------------------|-------|
| I0   | 9         | 8         | Minimum      | V0   | Double     | 1.6                    | 0.65  |
| I1   | 18        | 16        | Usual        | V1   | Adv. Double| 1.1                    | 0.63  |
| I2   | 25        | 25        | Minergie     | V2   | Triple     | 0.7                    | 0.5   |
| I3   | 35        | 35        | Minergie P   | V3   | Adv. Triple| 0.4                    | 0.37  |

Thermal conductivity: 0.03 $\frac{W}{mK}$ (wall) and 0.02 $\frac{W}{mK}$ (roof). Scenarios based on data from $>1600$ buildings.

In simulations where the refurbishment and the heating technology selection is planned at the neighborhood level, two additional technologies are allowed:

- Thermal exchange through pipelines, allowed only if the heating temperatures are identical. For domestic hot water, no thermal exchange is allowed. The shortest distance between the buildings is considered, and no obstacle is accounted for.
- A single seasonal storage is allowed. Heat exchanges with the seasonal storage are only possible if a connection between the storage and the building exists through a pipeline.

The MIP gap, which describes the precision of the optimization, is chosen to be 5%. The electricity produced by the system is sold to the electricity network.
3.4. Cost model
For each technology, the cost per year is the sum of the annualized investment costs and the maintenance costs. We then add the cost of fuel oil and electricity and we subtract the gain related to electricity production (Equ. 1). To annualized the investment cost, we use a capital recovery factor \((CRF)\). The \(CRF\) accounts for the years of usage \(n\) and interest rate \(i\) (~3% per year) as follow:

\[
CRF = \frac{i(i + 1)^n}{-1 + (1 + i)^n}
\]  

The detailed list of cost, adapted to the Swiss context, is available in [11].

3.5. Sets of constraints
We run the optimization on three different sets of constraints, listed below:

- Optim.0: The buildings are considered separately. Connections between the buildings and seasonal storage are not allowed.
- Optim.1: All technologies are allowed including heat exchange between buildings.
- Optim.2: CO\(_2\)-intensive technologies are not allowed (Fuel oil boilers and CHP). Heat exchange and seasonal storage are allowed.

4. Model results
In this section, we summarize the technologies selected by the optimizer for the two villages (represented in Figure 2 for village 2).

4.1. Insulation and windows
In all optimizations, the insulation kit I1 is selected for both villages. In our simulations, stronger insulation kits similar to Minergie standard are not selected because of their high investment costs. For the windows, triple-glazing (V2) or advanced triple-glazing (V3) is selected for all buildings in Optim.1 and Optim.2. In Optim.0, where buildings are considered separately, the selected windows vary between buildings, from V0 to V3.

4.2. Heat exchanges between buildings
For the optimizations where heat exchanges between buildings are allowed (Optim. 1 and 2), pipelines are always selected and buildings are connected to exchange heat.

4.3. Energy production
In Optim.0, where buildings are considered separately, oil boilers and heat pumps are used as the main heating technology for both villages. In Optim.1, heat pumps become the main heating technology in village 2 and their usage increases in village 1 even if cost is the only optimization goal. Indeed, heat pumps are more expensive to install, but cheaper to operate than oil boilers. Hence, heat pumps become more interesting financially if they are used intensively. As a consequence, the creation of a heat network in Optim.1 and 2 results in larger, cheaper heat pumps installed in one or two buildings instead of the multiplication of heating production units.

Photovoltaic panels are constructed in both villages for all optimizations. CHP is never selected.
4.4. Energy storage
Daily storage for hot water and/or space heating is installed in all simulations. Seasonal storage, with a volume between 21 and 33 m$^3$, is selected for both villages in all simulations where it is allowed (Optim.1 and 2), decreasing the peak load, and so the installed power of the heating equipment.

5. Analysis
5.1. Comparison with the realized solution for village 1
Since the realized refurbishment in village 1 has strong environmental goals, we compare here the outputs from Optim.2 with the realized solution. Insulation and windows are very similar in the optimized and realized solutions. The selected technologies are also comparable: Solar panels are widely used, heat pump is the main heating technology, seasonal storage is used, and all buildings are connected to share heat. However, the sizing shows some differences, notably the area of thermal panels and the volume of seasonal storage is larger in the realized solution than in the outputs from the optimization. Nevertheless, the optimized solution is close enough to the realized solution to consider the model realistic.

5.2. Comparison between optimizations
The annualized cost (Table 2) of the three optimizations with different sets of constraints is similar. The output from Optim.1 is 4.4% cheaper than Optim.0 in village 2 and 11% cheaper in village 1.

| Table 2. Annualized cost (CHF) for each set of constraints |
|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
|                             | Optim. 0  | Optim. 1  | Optim. 2  |
| ----------------------------|-----------|-----------|-----------|
| village 1                    | 94’000    | 84’000    | 90’000    |
| village 2                    | 173’000   | 166’000   | 170’000   |

We employ CO$_2$ emission as a proxy for environmental impacts. To estimate CO$_2$ emission, we use the emission parameters from the KBOB [13], the heating needs, and the technology selected by our optimization. As shown in Figure 3, CO$_2$ emission is markedly lower (~60% in
village 1) in Optim.1, when the buildings are connected together, than in Optim.0, where all buildings are considered separately.

![Graph](image)

**Figure 3.** CO$_2$ emissions of both villages using renewable electricity or usual Swiss consumer mix

6. Conclusion and outlook
The creation of a heat network between the buildings in combination with building refurbishments and improvement to the heating system results in similar overall costs while reducing drastically CO$_2$ emissions. The difference lies in the optimal use of solar energy, heat pumps and seasonal storage. Moreover, a coordinated planning of refurbishment could bring additional advantages such as scale economy for material cost. Hence, based on our simulations, planning refurbishment at the neighborhood scale seems to reduce heating needs and to support the achievement of the 2050 energy strategy.

References

[1] Bundesamt für Energie (BFE), 2018, Analyse des Schweizerischen Energieverbrauchs 2000-2017 nach Verwendungszwecken, Bern, Switzerland
[2] Bundesamt für Energie (BFE), 2018, Wichtigste Neuerungen im Energierecht ab 2018, Bern, Switzerland
[3] Chantrelle FP, Lahmidi H, Keilholz W, El Mankibi M and Michel P, 2011, Development of a multicriteria tool for optimizing the renovation of buildings, *Applied Energy*, 88, pp.1386-1394
[4] Salminen M, Palonen M and Siré K, 2012, Combined energy simulation et multi-criteria optimisation of a leed-certified building, *Proc. of Building Simulation and Optimization Conf.*
[5] Wang C, Kiliks S, Tjernström J, Nyblom J and Martinac I, 2017, Multi-objective optimization and parametric analysis of energy system designs for the Albano university campus in Stockholm, *Int. High-Performance Built Environment Conf., Procedia Engineering*, 180, pp.621-630
[6] Kaempf J, Robinson D, 2009, Optimization of urban energy demand using an evolutionary algorithm, *Proc. of the Eleventh International IBPSA Conf.*, pp.668-673
[7] Poumadère F, Rager J, Kaempf J, Kuchler F and von Gunten D, 2018 Dynamic thermal simulation and mathematical optimization as a retrofitting planning tool at the neighbourhood scale, In: 20. Status-Seminar Forschen für den Bau im Kontext von Energie und Umwelt (Brenet), pp.231-240
[8] Robinson D, 2011, *Computer Modelling for Sustainable Urban Design: Physical Principles, Methods and Applications*, (London: Earthscan)
[9] Li J, 2011, Agglomerative Connectivity Constrained Clustering for Image Segmentation, *Statistical Analysis and Data Mining*, 4, pp. 84-99
[10] Gurobi optimization LLC, 2018 *Gurobi Optimizer Example Tour*
[11] Rager J, Poumadère F, von Gunten D, Kaempf J and Kuchler F, 2019 OSCARS: Optimized energy network-based solutions compared to retrofitting scenarios Rapport final (submitted)
[12] Poumadère F and Kuchler F, 2014, RenQuart: retrofitting districts, In: 18. Status-Seminar Forschen für den Bau im Kontext von Energie und Umwelt (Brenet)
[13] KBOB 2009/1:2016, BFE (https://www.kbob.admin.ch/kbob/fr/home/publikationen/nachhaltiges-bauen.html)