Zurich, June 15-17 2016
Sustainable Built Environment (SBE) Regional Conference

Expanding Boundaries:
Systems Thinking for the Built Environment

ECONOMIC AND ENVIRONMENTAL ASSESSMENT OF BUILDING RENOVATION: APPLICATION TO RESIDENTIAL BUILDINGS HEATED WITH ELECTRICITY IN SWITZERLAND

B. Périsset[1], S. Lasvaux[1]*, C. Hildbrand[1], D. Favre[1], S. Citherlet[1]

[1] University of Applied Sciences of Western Switzerland (HES-SO), School of Engineering and Business Vaud (HEIG-VD), Laboratory of Solar Energetics and Building Physics (LESBAT), Yverdon-les-Bains, Switzerland

*Corresponding author; e-mail: sebastien.lasvaux@heig-vd.ch

Abstract

Following the Fukushima accident in 2011, Switzerland decided to start turning off the electricity coming from nuclear power plants as a part of an ambitious “Energy Strategy 2050” including better energy savings and efficiency of buildings and the development of renewable energies. In this new framework, one of the measures concerns the replacement of direct electric heating systems. It has been discussed in some Swiss cantons and increases the pressures on building tenants that use direct electricity as energy carrier e.g., for heating. However, from an environmental and economic point of view it is not clear yet whether it is better to renovate the building envelope, the electric heating systems or a combination of both. As several alternatives exist during a building renovation, the objective of this paper is to conduct an integrated economic and environmental assessment of four representative scenarios using the Life Cycle Assessment and Life Cycle Cost methodologies based on Swiss standards and cost data collected from manufacturers. From an economic point of view, results showed that the renovation of the electric heating system by a heat pump, solution often promoted by Swiss cantons, enables to get similar costs compared to the existing building. This solution is more interesting than the building envelope renovation or the switch to another heating system for which a technical room needs to be created. From an environmental point of view, the building envelope renovation is fundamental to lower the impacts. The partial renovation of the building envelope while keeping the direct electric heating system gives equivalent results compared to the only replacement of the electric heating by an air-to-water heat pump. Finally, this study shows that it is not always possible to be below the indicative values of the SIA 2040 standard “Energy Efficiency Path” (intermediate goals of the 2000-Watt Society) for the “Construction” and “Operational” aspects for building renovation.

Keywords:
Life cycle cost; life cycle assessment; residential buildings; renovation; electricity

1 INTRODUCTION

It is currently possible to design buildings with a nearly-zero energy consumption as well as buildings that produce more energy than they actually consume. By optimizing the choice of materials and integrated technical systems, these buildings can also present a low environmental impact. However, the situation is rather different for the existing building stock. When renovating a building, getting a substantial decrease of the environmental impacts while keeping the costs down offers quite a challenge. The choice of a financially and environmentally potent solution turns out to be rather complex. Within this context, a national project funded by the Swiss Federal Office for Energy (SFOE) was conducted to investigate low environmental impact renovations of single family houses and multiple dwellings. This project aimed at improving the knowledge on the economic and environmental aspects of energy related renovation solutions by taking into

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DOI 10.3218/3774-6_56, ISBN 978-3-7281-3774-6, http://vdf.ch/expanding-boundaries.html

account not only the operational energy consumption but also the outcome of a Life Cycle Assessment approach which integrates both building materials and technical systems. A methodology to perform building economic and environmental analyses was defined, which helps in the decision making process. In particular, the substitution of direct electric heating by another type of heating system requires substantial effort. Indeed, several renovation scenarios can be considered. The aim of this paper is thus to assess them according to stakeholders' practices in the building renovation sector to highlight the most cost-effective ones.

2 MATERIALS AND METHODS

2.1 LCA and LCC methodologies

An energy-related building renovation LCA methodology was used based on the IEA EBC Annex 56 project [1]. The system boundaries and the calculation rules are compliant to the SIA 2032 [2] technical book recommendations used for the Minergie-ECO® standard. It only takes into account impacts linked to materials of the construction elements and technical systems part of the energy-oriented renovation. Environmental impacts are evaluated through two separate indicators: non-renewable primary energy (CED_{NRE}) and greenhouse gases emissions (GWP). The environmental data is taken from the KBOB LCA recommendations list (2012 version) [3].

The financial calculation is based on the SIA 480 [4] standard. Federal and cantonal renovation subsides are taken into account. Materials costs were obtained through manufacturers and suppliers. They are valid for the location of the buildings studied but could drastically differ for building situated in other areas. Regarding energy-related costs, the calculation method takes into account the initial investment, the maintenance costs as well as the cost of the energy vectors. No annual increase of the energy cost was considered for the heating costs. Given the high variability of the costs, also linked to the investment method (loan rates, etc.), an uncertainty margin of 20% was used for the LCC results.

The building lifespan is set at 60 years (in agreement with IEA Annex 56 recommendations). Materials and technical systems replacements are considered using lifespans close to SIA 2032 guidelines [2]. In all case studies, heating system efficiencies are compliant with the SIA 2040 technical book [5]. The only exception is the heat pump, which COP has been the object of a separate evaluation.

2.2 Building case studies

Two existing buildings built in Switzerland in the early 1980ies and heated with direct electricity heating are used as case studies. The first one is a single family building (SFB) occupied by the landlord and the second one is a multi-family building (MFB) occupied by the tenants in the Vaud Canton. Indeed, in Switzerland, 38% of the housing are occupied by the landlords and 62% by the tenants [6]. Considering these two situations (owning and renting) enable to improve the study's representativeness.

First, each existing building is assessed before renovation (reference case). Then, LCA and LCC are done through an energy-related building renovation according to the four strategies defined in section 2.3. Figure 1 presents the pictures of the two case studies.

Fig. 1: Visualisation of the SFB (left) and MFB (right) case studies.

2.3 Renovation strategies

Four different renovation strategies are considered in this study:

- *Strategy A*: Substitution of direct electric heating by other systems (e.g., heat pump, natural gas boiler, pellets) without renovating the building envelope (scenario only relevant if the thermal envelope is not too outdated).
- *Strategy B*: Renovation only of the building thermal envelope
- *Strategy C*: Renovation of the building thermal envelope and replacement of the heating system.
- *Strategy D*: Renovation of the building envelope and direct electric heating system connected to a photovoltaic installation to balance the annual electricity consumption from the grid and lower the environmental impacts.

Within strategies A and B, different individual scenarios were first compared in preliminary studies to limit the combined scenarios within strategy C. These preliminary assumptions are presented below.

For the SFB case study, as the thermal envelope is not outdated, the substitution of the heat production system (strategy A) was preliminary studied. Different types of heating systems were compared including air-water heat pump (HP), fossil solutions or the pellets. A preliminary study shows, by taking into account the costs and the environmental impacts generated throughout the building lifespan and the technical constraints, that an air-water heat pump is a better choice than oil, natural gas or pellets. Similarly, regarding the

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renovation of the thermal envelope (strategy B), the preliminary study led to add an external EPS insulation to the massive walls. The first storey walls that have a wooden structure were improved using EPS between the wooden beams and the roof was insulated with PUR. The addition of these renovation measures make the building comply with the Swiss standard SIA 380/1 renovation requirements [7]. In this paper, the optimal scenario within strategy B includes also the addition of a 2-IV glazing windows. Renovation through strategy C finally integrates both renovation of the thermal envelope (as in scenario B) as well as the replacement of direct electric heating by an air-water heat pump.

For the MFB case study, considering the state of its thermal envelope (visual aspect and thermal performance) and in agreement with the building owner, a renovation of the external insulation is required, excluding strategy A for this case study. Then, numerous alternatives within strategy B were compared for the external walls: ventilated or non-ventilated facades with various insulation materials. The optimal scenario finally corresponds to a ventilated façade with glass wool insulation and comply with the SIA380/1 renovation standard [7]. Finally, several renovations scenarios within strategy C were assessed considering different heat production systems: air-water heat pump and wood pellets (presented in section 3.2) as well as natural gas, light fuel oil and a geothermal heat pump (results not presented here due to paper length limitation).

	SFB	MFB
Strategy A	X	
Strategy B	X	X
Strategy C	X	X
Strategy D	X	X

Tab. 1: Renovation strategies considered for the SFB and MFB case studies.

For both case studies, a renovation scenario based on strategy D was also analysed by combining, next to the renovation of the envelope, a direct electrical heating with PV panels. Average solar cover percentages were retrieved from the Swiss Federal Office for Energy (SFOE) solar thermal guidelines and photovoltaic pre-sizing tools [8; 9] with respectively 60% of DHW cover (for SFB and MFB) with solar thermal collectors solar and 13% (for SFB) and 74% (for MFB) heating cover based on PV panels.

3 RESULTS

3.1 SFB case study

Figure 2 presents the LCC results while figure 3 presents the LCA results (in terms of GWP and CED_{NRE} indicators). Results are presented in Euros assuming a 1:1 exchange rate with the Swiss Francs (CHF). For all the following graphics, results of the optimal scenario within a strategy is abbreviated with the letter of the strategy (A, B, C or D) complemented if relevant by the name of the heating system in brackets. Finding a global optimal solution that minimize both costs and all environmental impacts is not possible. Financial results on top of Figure 2 show that the substitution of the direct electric heating by an air-water heat pump, without renovating the thermal envelope, leads to lower yearly costs than the reference case. In all other renovation scenarios yearly costs are found higher than the reference case. Due to the very low cost of the heat pump, the total cost of this optimal scenario is found similar to the renovation cost of the thermal envelope (red bars on other variants). All other scenarios generate yearly costs which are situated within that 20% uncertainty margin. Renovation according to axis C leads to 25% to 35% over costs while strategy D is even more expensive. For all these variants, expenditure linked to the improvement of the thermal envelope performance is never compensated by the money saved through the reduction of the energy consumption.

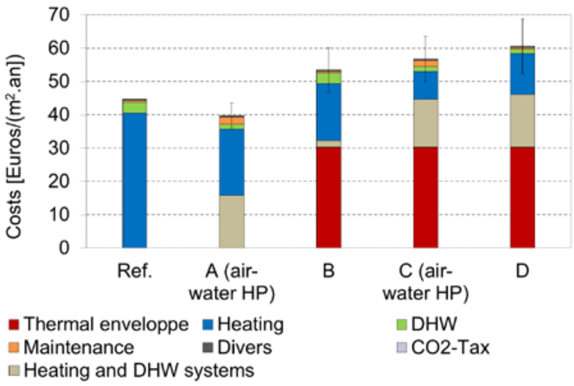

Fig. 2: LCC results for the SFB case study.

From an environmental perspective (Figure 3), replacing the electrical heating with an air-water heat pump (without touching the thermal envelope) reduces GWP and CED_{NRE} impacts by half. This scenario's environmental performance is on par with other solutions from axis "C" but offers a much preferable solution from a financial point of view. When neglecting financial constraints, the optimal scenario is a complete renovation of the thermal envelope paired with the installation of an air-water heat pump. That solution reduces the greenhouse gases emissions by two thirds and non-renewable energy consumption by 75%.

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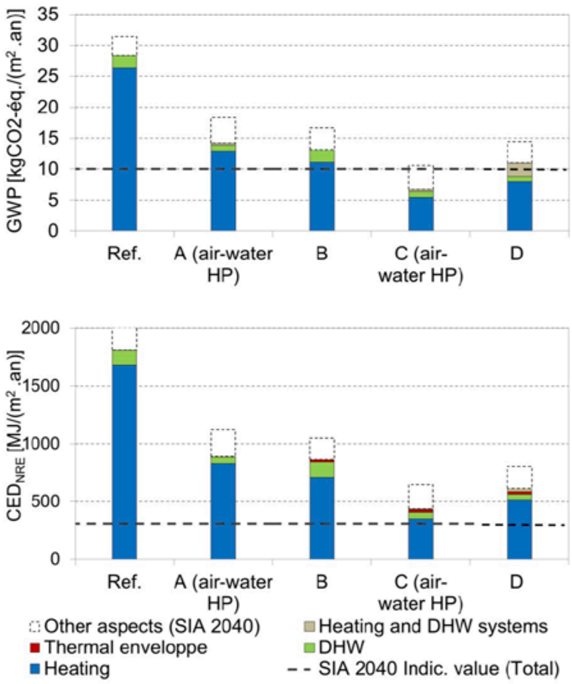

Fig. 3: LCA results expressed in GWP (top) and CED_{NRE} (bottom) for the SFB case study.

3.2 MFB case study

LCC results on Figure 4 show that all renovation scenarios generate annualised costs higher than the existing building.

The solution with the lowest over costs (around 7%) consists of keeping the existing heat production systems and renovating the thermal envelope (strategy A). Looking at the two scenarios from strategy C, the air-water HP is better (with 7% over costs) than the wood pellets solution where annualised costs are about 30% higher compared to the existing building. This can be explained by the high investments required for the technical systems (new boiler and hydraulic distribution network needed). Interestingly, when taking into account the uncertainty margin of 20% linked to the variability of the investment and maintenance costs, it is not possible to determine with confidence any optimal renovation solutions.

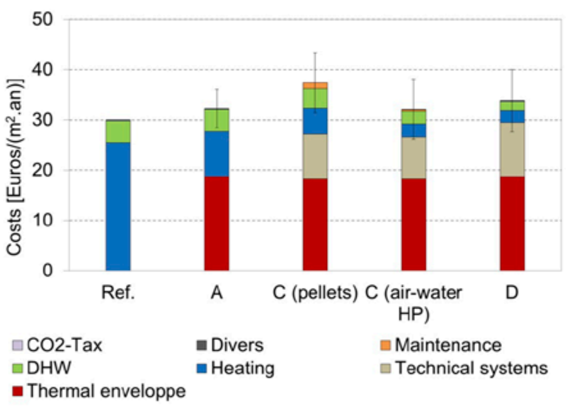

Fig. 4: LCC results for the MFB case study.

LCA results (Figure 5) expressed in GWP and CED_{NRE} are similar than those from the MFB case i.e., adding thermal insulation and replacing the electrical heating by an air-water heat pump (strategy C) is the best solution when trying to minimize greenhouse gases emissions and the non-renewable primary energy consumption.

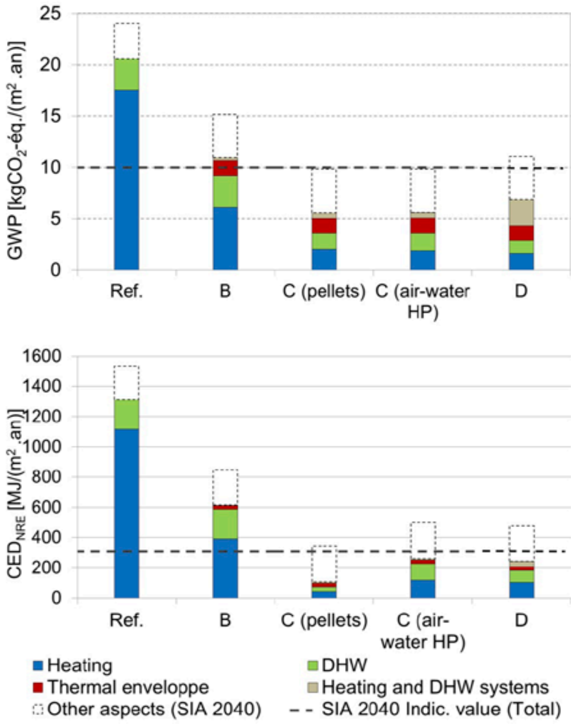

Fig. 5: LCA results expressed in GWP (top) and CED_{NRE} (bottom) for the MFB case study.

The strategy C (air-water HP) provides a good compromise as its yearly costs are quite similar to the initial situation. If a storage space can easily be found, a pellets boiler offers an interesting alternative. Environmental performance is also very high but yearly costs are around 10% superior. As there is an important amount of uncertainty linked to the financial data, this small costs difference falls within the uncertainty margin.

3.3 Comparison of LCA results with the SIA 2040 indicative values

The SIA 2040 technical book defines indicative and target values to move towards a 2'000-Watts Society (resp. a 1 ton CO_2-eq Society) by defining intermediate goals for 2050 [5]. The SIA 2040 provides individual target values for building construction, operation, occupant's mobility for both greenhouse gases emissions and non-renewable primary energy consumption. In this paper, only the "construction" and "operation" SIA 2040 target values were calculated. Figure 3 and 5 present the results. For the operational aspects, default values proposed in SIA 2040 were used to take into account of the electricity needed for auxiliary, ventilation, lighting, sanitary and operating equipment. These end-uses are referred as "Other aspects (SIA 2040)" in Figure 3

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and 5 while the SIA 2040 target value for construction and operation is displayed using a black dotted line.

Comparisons of the LCA results with the SIA 2040 target values showed:

- *For the SFB building*: none of the scenarios studied reaches the intermediate goals of the 2'000-Watts Society, both for CED_{NRE} and GWP. The best scenario in terms of CED_{NRE} and GWP (Renovation of the thermal envelope combined with an air-water HP) is also far from the total SIA 2040 indicative value.
- *For the MFB building*: two scenarios are below the SIA 2040 target value regarding CED_{NRE} while none of the scenarios comply with GWP target value. However, the "pellets" scenario, which consists of a renovation of the thermal envelope combined with wooden pellets heating, is very close to complying with SIA 2040 target values.

4 DISCUSSION AND CONCLUSION

For the financial indicator, the replacement of direct electricity heating systems in Swiss residential buildings is not interesting if a storage or a technical room needs to be built for the new heating system. The replacement of the direct electricity heating by a new air-water heat pump without renovating the envelope, solution often recommended by the Swiss cantons, allows a little financial pay back compared to the building before renovation. This finding is in line with previous studies such as Risholt and al. [10]. This choice remains robust even when assuming an uncertainty margin of 20% linked to the variability of the investment and maintenance costs. However, it is important to recall that the renovation of the building envelope is often a needed action to maintain the building in a good state (as shown for the MFB case) while it is not the case for the replacement of the heating system. In all other cases, this study has shown that the cost of renovation is never compensated by the money saved through the reduction of the energy consumption. In both case studies, the thermal envelope renovation is a costly operation which will not be paid back within the 60 years of the building lifespan. The outcomes of this study has different consequences depending on the type of building occupants. On the one side, the over costs will be more easily paid back in MFB occupied with tenants as the landlord will be able to adjust the monthly rents following the renovation of the building. On the other side, this situation will not happen for a building occupied by a landlord as it was the case in this study for the single-family building.

From an environmental point of view, the thermal building renovation is important to lower the total impacts including the operation heating demand. The share in the environmental impacts due to the added insulation materials remain small compared to the heating energy savings. This finding is in line with previous studies except the study from Gustavsson L. and Joelsson A. [11]. In that case, they found that the choice of energy supply system affects more the environmental impact than the energy-efficiency measures to improve the building envelope. This difference between our study and their study can be explained by different building factors (U-values, efficiency of technical heating systems) or database environmental impact (materials and energies).

In this paper, it was also found that the renovation of the envelope combined with the maintenance of the direct electricity heating is similar to the replacement by a heat pump without renovating the envelope. Results compared with the intermediate 2050 goals of the 2'000-Watts Society show that it is not easy to get results lower than the combined indicative values for construction and operation in the specific case of residential buildings' renovation. As the mobility related impacts were not included in this study, it is not possible to conclude on a broader system boundary including mobility aspects (2'000-Watts Society requirements). Furthermore, additional electricity consumption linked to ventilation, auxiliary, lighting and operating equipment has been taken into account using default values provided by SIA 2040. A more accurate evaluation of those energy needs would perhaps slightly scale down energy-related impacts.

Combined LCA and LCC results have shown that 2000-Watts Society intermediate 2050 objectives are not easy to reach in a cost-effective way when renovating existing buildings. It does not mean that these buildings should not be renovated as most renovation scenarios studied generate a drastic reduction of primary energy and CO_2 emissions for the operational energy. Finally, besides technical, economic and environmental constraints, it is also important to include in the assessment social impacts induced by the renovation and also the co-benefits of the renovation concerning the well-being of occupants, the potential improved indoor air quality and other similar aspects.

5 ACKNOWLEDGMENTS

The authors of this paper would like to gratefully thank the Swiss Federal Office for Energy (SFOE) for its financial support through the ECO Reno research project.

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