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Earth Plastered Wall Heating as a Low-Emitting, Cost-Effective and Robust Energy System for Building Renovation

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Abstract. Renovation of the building stock in Europe is urgent to decrease the environmental impact from the building sector and meet the United Nations climate action goals. However, it is often hard to define a robust scenario for a renovation due to numerous uncertainties, which occur during the production, operation and end-of-life stage. One can cite the loss of performance of insulation and heating systems, the replacement time of installation or the future energy prices as well as the future climate. The replacement of oil boilers with heat pumps has shown a good performance regarding costs and greenhouse gas emissions. However, due to the flow and return temperature differences, often the current heat distribution system needs to be replaced as well, which is normally done with conventional radiators or floor heating. In this paper, we analyse a new possibility of a heat distribution system with earth plastered wall. We develop a methodology on the integrated assessment of life cycle assessment (LCA) and life cycle cost analysis (LCCA) for the renovation scenarios and adapt the analysis of the heat pump renovation solution with conventional radiators system and the earth plastered wall for two typical residential buildings located in Switzerland. Through rigorous statistical treatment, we then propagate the possible sources of uncertainty and perform the uncertainty quantification using polynomial chaos expansion to compare the distributions of two outcomes. The results show that the solution with the earth plaster has lower overall environmental impacts and costs. It has also been noticed that the solution with the earth plaster is more robust in investment cost and embodied emissions compared to the solution with the conventional radiators.

1 Introduction

The building sector is responsible for 40% of the greenhouse gas (GHG) emissions in the world (UN Environment and IEA, 2018). The largest share of these emissions in the existing building stock is coming from the operational part. Therefore, the renovation of the building stock is essential to decrease the amount of GHG emissions. LCA and LCCA are used to evaluate the overall amount of the GHG emissions and costs of the building's life cycle from the material production, operational energy to the replacement and end of life.

However, it is often hard to select a proper renovation strategy due to numerous uncertainties during the building life. In LCA and LCCA, such uncertainties include the service life of building materials, future climate, embodied impact of the materials and their initial cost, interest rate, amongst others. It has been shown that these uncertainties highly affect the result and lead to unexpected output

(Macdonald, 2002; Häfliger *et al.*, 2017; Favi *et al.*, 2018). It has also been shown that the variability due to uncertainties in two solutions is sometimes higher than the difference between the solutions in a deterministic context (Fawcett *et al.*, 2012). This raises questions about the validity of the results of such deterministic analyses. Therefore, uncertainty analysis is needed to get reliable results. In a previous research, we have found out that the most reliable, cost-effective and environmentally friendly renovation strategy is the replacement of the heating system by a wood boiler or heat pump (Galimshina *et al.*, 2020). Heat pumps have shown a good performance in terms of environmental impacts (Finnegan, Jones and Sharples, 2018). However, replacing a gas or oil boiler with a heat pump needs to ensure to reach lower flow temperatures in order to reach a sufficient coefficient of performance (COP). This might require to decrease the heating demand by insulating the building envelope more efficiently (external walls, ground floor or the roof). If the heating demand decrease is not feasible or sufficient, it may also require the replacement of the whole heat distribution system in a building. The replacement of a heat distribution system is especially problematic when floor heating is installed in a renovation of a multifamily house, because the tenants often need to move out during the process. In this paper, we consider two possible heat distribution systems – conventional steel radiators and the earth plastered heating wall.

Earth has been used as a construction material for many years and has many applications in a building (Mileto, Vegas and Cristini, 2006). Clay boards and plasters can be used as an alternative to gypsum, lime and cement-based building boards (Schroeder, 2014). Depending on the thickness, the boards have various applications – structure, cladding, partition walls and heating or cooling elements. A heating or cooling wall element is a heat distribution system, which is installed directly on the wall and works as a radiator. The system is similar to floor heating, which includes plastic or copper tubes covered by a layer of cement screed. However, the clay wall plaster has an advantage in a renovation process that it does not require to move out the furniture and residents do not need to leave the building during the process. Usually the thickness of the installed elements is about 2.5 cm.

Besides being environment-friendly and locally available material, earth has also an advantage in thermal properties (Clayworks, 2020). It has been shown that temperature control and air quality are significantly improved in the earthen buildings due to the hygrothermal properties of earth (Liuzzi *et al.*, 2013; McGregor *et al.*, 2016; Fabbri and Morel, 2019). The earth has high thermal conductivity, which allows for a faster heat transfer. Moreover, due to the clay plaster, the sound from the adjacent rooms is reduced, which is often a problem in multifamily houses (Variotherm, 2020a).

In this paper, we evaluate the possibility of using the earth heating wall system as a heating distribution and compare it to conventional steel radiators. We evaluate two building representatives from two construction periods in Switzerland and compare the investment costs, embodied GHG emissions, overall life cycle costs and life cycle GHG emissions.

2 Methodology

The methodology follows four steps. First, the integrated analysis of LCCA and LCA is created. The analysis includes the production, operation, replacement, and end of life stages. The metrics of the assessment are the total costs in Swiss Francs (CHF) and the overall Global Warming Potential (GWP) in kgCO_2eq. for the building' lifetime. The latter is assumed to be 60 years according to the Swiss regulations (SIA, 2010). The functional unit refers to a surface of 1 m^2 of the building during its lifetime. The detailed procedure of the analyses is explained in (Galimshina *et al.*, 2020).

After the integrated assessment was created, the renovation scenario is defined in the second step. In this paper, we consider the replacement of the gas boiler with the heat pump and examine two possibilities of the heat distribution system since the temperature difference is getting lower – radiators with the bigger surface or the plastered wall heating. Two systems were added to the workflow to evaluate the overall cost and environmental impact based on the power provided.

The plastered wall heating represents a heat distribution system, which includes the plastic or aluminum pipes installed directly on the wall using the mounting system, which are afterwards covered with earth plaster. The system installation process is shown in Figure 1. The system is installed in place and flexible for both small and large surfaces. No maintenance is required and, in case of the pipe leakage, the replacement can be done in place and new plaster is applied directly.

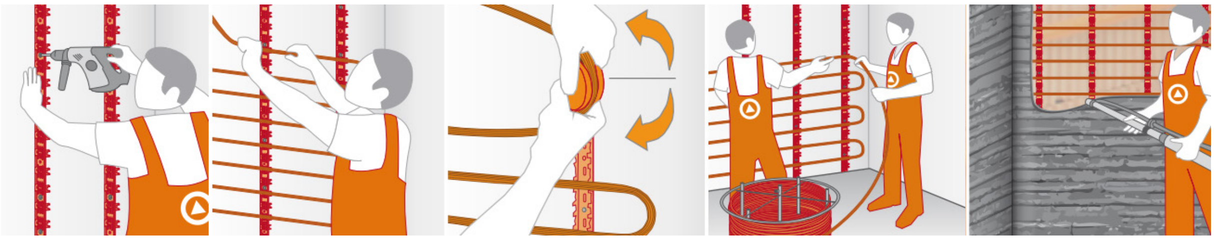

Figure 1 – Installation process of the plastered wall heating (Variotherm, 2020b).

The plastic tubes with 16 mm diameter are considered in this study. Overall, the thickness of the system is considered to be 25 mm. The embodied environmental impact of the earth plaster is considered to be 0.34 $kgCO_2eq/m^2$ (KBOB, 2016). The environmental impact of the 16 mm diameter tubes is considered to be 4.22 $kgCO_2eq./kg$, 0.07 kg/m (Lewis, 2018). The distance between the tubes is considered to be 20 cm. The environmental impact of the steel for the radiator is taken as a blast furnace steel with 2.3 $kgCO_2eq./kg$. The reference service life of both systems is set to 25 years. The embodied environmental impact and cost for the earth panels and conventional radiators are presented in Table 1. The provided power output is higher for radiators and therefore, smaller surface is needed.

Table 1 – Embodied environmental impact and investment cost of the clay wall heating panel and a radiator

Type of heat distribution	Embodied impact ($kgCO_2eq./m^2$)	Initial cost (CHF/m^2)	Power (W/m2)
Radiator	27.6	460 (incl. labor cost)*	483 (under EN 442 conditions)
Earth panel	1.8	110 – 150 (lncl. labor cost)	80

*depends on the type of radiator

In step three, uncertainty quantification is performed. Uncertainty quantification aims at identifying all the sources of uncertainty in the model and quantifying the overall effect of the uncertain parameters to the model output e.g. LCCA and LCA. In this work, we use crude Monde Carlo simulation together with *polynomial chaos expansions (PCE)* as a method for uncertainty analysis. *PCE* are used as a surrogate model as they allow efficient representation of the model response at a lower cost and hence dramatically reduce the computational cost of the uncertainty analysis. The details for practical application of PCE can be found in Le Gratiet *et al*. (Le Gratiet, Marelli and Sudret, 2017).
Finally, once the results for the uncertainty propagation are obtained, the two systems and two buildings are compared in terms of embodied impact, investment costs, LCCA and LCA.

Case study

In this paper, we consider two reference buildings. They represent multifamily houses located in Western Switzerland from two construction periods – 1910 and 1972. The basic details about the building are presented in the Table 2. The heating demand before renovation is presented and does not change after application of a new heat distribution system as no envelope renovation is considered.

Table 2 – Basic information on the case studies

Location	Year of construction	Heating demand ($kWh/m^2,a$)	Current heating system	Energy reference area (m^2)
Lausanne, Switzerland	1910	141.3	Gas boiler	1563
Cossonay, Switzerland	1972	91.3	Gas boiler	1446

Uncertain parameters

During this study, the uncertain parameters were identified and modelled for all the stages of the analysis following the methodology described in (Galimshina *et al.*, 2020). In Table 3, the parameters associated to the earth heating panel and radiators are shown.

Table 3 – Uncertain parameters associated to the earth heating panel. They describe the possible variations around the corresponding nominal values.

Model parameter	**Parameters**	**Distribution**	**Source**
Embodied impact radiator [%]	[-30,30]	Uniform	(Chen *et al.*, 2010; Gomes *et al.*, 2013)
Embodied impact earth plaster heating [%]	[-30,30]	Uniform	
Initial cost radiator [%]	[-20,20]	Uniform	(SIA 480, 2016)
Initial cost earth plaster heating [%]	[-20,20]	Uniform	

3 Results

The results of the total LCA and LCCA for two solutions are shown in the Figures 2-3. As it can be seen, the results of the earth plastered heating for both buildings are lower than those of the conventional radiator for all the metrics *i.e.* investment cost, embodied GWP, overall life cycle costs and life cycle GWP, even while considering higher surfaces due to the lower power output. It can also be noticed that the uncertainty range for all the metrics is larger for the radiator system than for the earth wall panels.

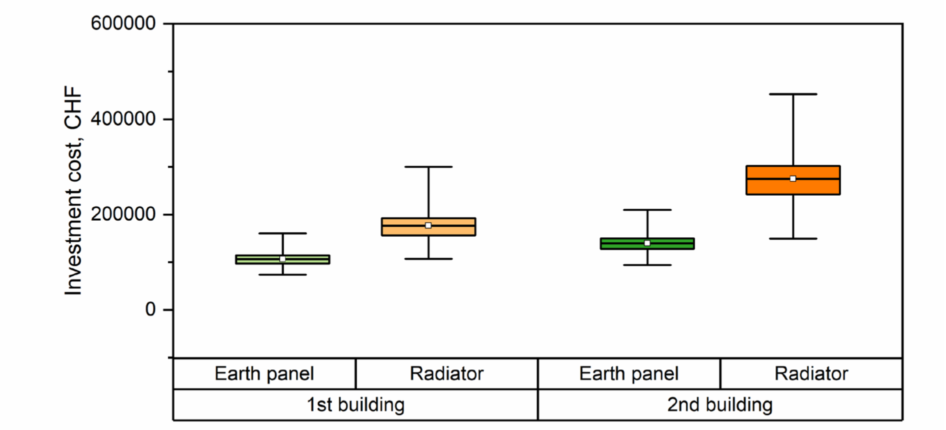

Figure 2 – Investment costs comparison

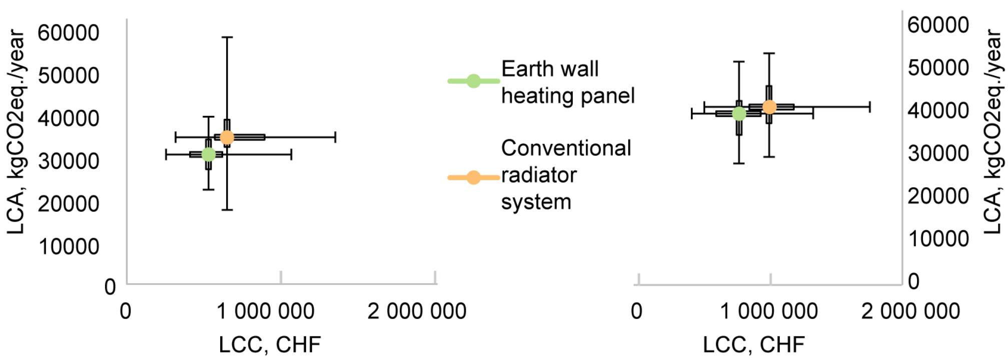

Figure 3 – Total costs and environmental emissions for a building 1 (on the left) and building 2 (on the right)

As it can be seen from the results, the difference for the investment cost and embodied GWP for the two systems is higher than for the overall life cycle costs and life cycle GWP. This can be explained by the operational energy having higher share than investment cost and embodied GWP for both LCCA and LCA.

4 Discussion

In this paper, we compared two solutions for the heating distribution system replacing the old heat generation by a new air-to-water heat pump. The results show that earth plastered wall heating yield better performance than the conventional radiators in terms of life cycle GWP, life cycle costs, initial cost and embodied emissions even though the power output is considerably lower.

In the traditional renovation scenario, the heating demand is normally decreased by renovating the building envelope. However, this is not enough in a view of the GHG emissions perspectives as the main influential parameter is the type of heating system (Galimshina *et al.*, 2020). Once considering only the heat pump without decreasing the heating demand, the heat distribution needs to be replaced due to the lower temperature differences and therefore, higher radiators` surface needed. This is the main obstacle for the heat pump as a single renovation measure since the replacement of the radiators is an expensive and carbon intensive solution. In this paper, we have shown that earth is the climate-friendly and cost-effective solution when applied in a building retrofit and potentially can be applied on a larger scale.

It has been shown that low temperature heating might improve both the thermal comfort and indoor air quality (Myhren and Holmberg, 2008; Sevilgen and Kilic, 2011; Rhee and Kim, 2015). Wall heating is using radiant heat, which warms up a room without causing a draught. Earth heating plastered wall also provide a significant improvement for the air quality due to the hygrothermal behavior (Liuzzi *et al.*, 2013). Therefore, such panels are a good alternative to conventional radiators in a building retrofit process. It should also be noted that earth heating can be easily repaired by taking out the damaged or cracked material and replacing it with a new earth plaster. The latter is itself easy to replace and has a high recycling rate.

It is clear that the uncertainty quantification is required to get reliable results. As the results show, even within the 1st and 3rd quartiles, the variation can be high and can lead to unexpected output if not considered in the study. For a more realistic analysis and considering the long building lifetime, the future economic, environmental and climate parameters need to be included as well.

5 Conclusion

A statistical method using surrogate model was applied to a renovation scenario of two residential Swiss buildings. The renovation scenario included the replacement of the old boiler by a heat pump and the heat distribution system as an earth plastered heating wall or the conventional radiator system. The results show that the earth plastered walls have lower overall costs and GHG emissions, and show a potential to be applied on a larger scale. Besides having a very low energy use and being available locally without preprocessing, the earth also has good thermal qualities. The results of the paper show the potential of using earth in a building renovation process.

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