Conference Paper

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Publication Date:
2013

Permanent Link:
https://doi.org/10.3929/ethz-a-010041375

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Balancing Active and Passive Building Components to achieve Minimal Greenhouse Gas Emissions in Refurbishment Projects

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Abstract

There exist active and passive components for refurbishment projects to reduce greenhouse gas emissions (GHG). The dilemma is that both require the installation of components, which come with a certain level of embodied GHG emissions. Additionally, the purchased power to operate the building also comes with specific GHG emissions. We developed a method to assess the equivalent annual GHG emissions of different combinations of active and passive components for a building with a heat pump heating combined with a ground source heat exchanger (GSHX). We applied this method to a reference model and determined a combination of insulation thickness and depth of GSHX that provides the lowest total GHG emissions. We found that this combination can considerably deviate from the currently recommended insulation thickness based on regulations regarding energy savings in refurbishment projects. As a consequence, refurbishment projects towards minimal or zero GHG emissions cannot be achieved by a normative approach, but require an assessment as proposed in this study.

Keywords – greenhouse gas emissions, active and passive building components, balance, refurbishment, embodied greenhouse gas emissions

1. Introduction

It has been widely recognized that the anthropogenic impact on the environment causes climate change. The existing building stock of Switzerland is accountable for a large share of the annual equivalent generated greenhouse gas emissions (GHG_e/a) of this country. Thus, the refurbishment of the existing buildings towards zero emission buildings is vital. However, the paths to achieve considerable lower GHG_e/a emissions are highly discussed. In general, there exist at least four strategies for reducing the GHG emissions of buildings in temperate climate of Europe.
1. **Reducing the primary energy demand.** This is the passive strategy targeting the annual heating and cooling demand. Examples: Additional layers of insulation or the replacement of windows increase the thermal resistance of the building envelope and reduce the annual heating demand. Controlled ventilation systems reduce the heat transfer. Managing systems reduce the household electricity demand for lighting etc.

2. **Combining high and low exergy in heating systems.** This is the active strategy targeting the efficiency of heating and cooling process. Examples: Free ambient heat from air, water and ground or recovered heat from processes with relatively low exergy can be combined in a heat pump with high exergy (preferable in form of electricity) to provide space heating or the generation of hot water. The efficiency of this heating depends on the temperature lift in the heat pump process in general and specifically on the efficiency of the machine.

3. **Substituting the energy carrier or building materials**
   Example: By choosing the mix of the electricity provided to a building, the specific GHG emissions per kilowatt electricity can be reduced. Choosing building material or construction methods that come with less embodied GHG emissions, but provide the same benefit (i.e. same thermal resistance) also allows substituting the emissions.

4. **Compensating GHG emissions with Emission Trading Certificates**
   Example: Offsetting the GHG emissions generated on site in areas beyond the systems boundary allows for a global reduction of the GHG emissions without changing the building itself. Leung et al. explicitly discuss the problematic of this approach [1]. This is not subject of this paper.

Applying the first strategy, the GHG emissions can considerably be reduced in buildings operating with an oil-fired heating system. This strategy focus on the reduction of the annual heating demand. However, when refurbishing buildings operate with heating system of a heat pump in combination with a ground source heat exchanger (GSHX), not only the annual heating demand matters, but also the efficiency of the heating system. This is expressed with coefficient of performance of the heat pump process (COP) or more precisely as energy efficiency ratio of the overall system (EER), which includes the electricity demand from other components with a power demand (auxiliary pumps etc). In this case the second strategy also applies. Furthermore, substituting the primary energy carrier, by choosing an electricity generation with lower specific emissions, can considerably reduce the overall GHG emissions of a system, as presented as the third strategy.
The objective of this study is optimizing the reduction of GHG emissions in a refurbishment project with these three strategies. This requires balancing the benefit that passive building components provide in form of insulation material with the benefits that active components provide in form of an efficient heat pump system. Different thicknesses of the insulation material affect the annual heating demand and consequently the required size of the heat pump and the GSHX. However, the insulation and the GSHX affect the overall amount of GHG emissions as both come with embodied GHG emissions.

As a result, a lifecycle assessment is required that includes the embodied GHG emissions of the components (insulation, borehole, heat pump etc) and the direct GHG emissions generated in the operation of the building.

2. Model

The considered building represents an average two story, single-family home in Zurich, Switzerland. The low insulated brick building has a heated floor area of 140m², which will, from here on, be referred to as energy reference area (ERA). The model is basically designed according to a building described in the report from Dott et al. for the IEA SHC Task 44/HPP Annex 38 [2]. This report provides further information regarding the dimensions, materials, loads etc. of this model. Figure 1 illustrates the effect that additional layers of insulation to the opaque wall have on the annual heating demand \(Q_h\) and the peak heating power \(q_h\).

This heating demand is provided by a heat pump system in combination with a GSHX. The required electricity to operate the heat pump comes from the national grid. Three power mixes with different specific GHG emission rates exist. Two insulation materials with different embodied GHG emissions have been considered (expanded polystyrene, EPS, and cellulose wall boards, CWB). It is assumed that the installation of the heat pump with hydronic radiant floor heating requires dismantling a condensing boiler system and radiators in the existing building, which has been considered as indirect GHG emissions due to deconstruction and the end of life phase of the components.

Table 1 lists the relevant data regarding the wall insulation, based on information from the econinvent database [3], and Table 2 the specific GHG emissions regarding the power mixes.
Figure 1 Maximal annually heat demand and the peak heat demand

<table>
<thead>
<tr>
<th>Material</th>
<th>GHG&lt;sub&gt;e/a&lt;/sub&gt;</th>
<th>Therm. Resistance R</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molded expanded polystyrene (EPS)</td>
<td>37 [g CO&lt;sub&gt;2&lt;/sub&gt;/cm]</td>
<td>0.25 [(m&lt;sup&gt;2&lt;/sup&gt;·K)/cm]</td>
</tr>
<tr>
<td>Plaster finish</td>
<td>408 [g CO&lt;sub&gt;2&lt;/sub&gt;]</td>
<td>0.02 [(m&lt;sup&gt;2&lt;/sup&gt;·K)/cm]</td>
</tr>
<tr>
<td>Cellulose wall insulation (CWB)</td>
<td>9 [g CO&lt;sub&gt;2&lt;/sub&gt;]/m&lt;sup&gt;2&lt;/sup&gt;</td>
<td>0.25 [(m&lt;sup&gt;2&lt;/sup&gt;·K)/cm]</td>
</tr>
<tr>
<td>Wood construction</td>
<td>602</td>
<td>0.03 [(m&lt;sup&gt;2&lt;/sup&gt;·K)/cm]</td>
</tr>
</tbody>
</table>

Table 2 Specific annual equivalent GHG per purchased electricity unit

<table>
<thead>
<tr>
<th>Standard Swiss power mix</th>
<th>“solar top” power mix</th>
<th>“eco power” mix</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.151 kg CO&lt;sub&gt;2&lt;/sub&gt;/kWh&lt;sub&gt;el&lt;/sub&gt;</td>
<td>0.078 kg CO&lt;sub&gt;2&lt;/sub&gt;/kWh&lt;sub&gt;el&lt;/sub&gt;</td>
<td>0.011 kg CO&lt;sub&gt;2&lt;/sub&gt;/kWh&lt;sub&gt;el&lt;/sub&gt;</td>
</tr>
</tbody>
</table>

Based on the ecoinvent database, the embodied GHG emissions of a 10kW brine/water heat pump are 1687kg CO<sub>2</sub>, which includes the materials used for production, the transport of these materials, energy and water needed for production and the emissions of refrigerant (R134a) during production and scrapping. The same database is used to determine the embodied GHG emissions due to the installation the double u-tube borehole. The backfilling in this study is assumed to be a regular bentonit-cementitious material. The brine is assumed to be a 25-35% ethylene-glycol mixture. It has further been assumed that the ground allows regular drilling, which requires 2.5L of diesel per running meter borehole.
3. Method

The annual equivalent GHG emissions are calculated for each considered refurbishment strategy. The GHG emissions generated in the operation of the building are added to the embodied GHG emissions of the insulation material and the components of the heating system, as shown in equation (1). The embodied GHG emissions of the building components depend on the GHG emissions generated during harvesting, production, transportation, construction, deconstruction and the recycling of a component. The direct GHG emissions depend on the primary energy demand and the used primary energy carrier.

\[
GHG_{e,a}(i, k) = \sum_{i} \frac{GHG_{mat, i}}{lc_i} + \sum_{k} \int_{t=0}^{a} ec_k \cdot EE_k(t) dt
\]  

(1)

For simplification, we assume that the annual equivalent GHG emissions from each component, \(GHG_{mat, i}\), equals the totally generated GHG emission during its life divided by its lifespan \(lc_i\) in years of a component. The information regarding the materials is based on the ecoinvent database. The GHG emissions from the building operation depend on the total end energy demand \(EE_k\) of each active component \(k\) generated in the period of a year and the specific coefficient \(ec_k\) related to the direct and indirect equivalent GHG emissions generated for the transformation and conversion of the primary energy source to one unit of the energy carrier.

4. Building simulation

The building operation is simulated with two programs. The software TRNSYS [4] is used to determine the annual heating demand and also to control room temperatures and temperatures of the heating system. Based on these results, the relevant information is imported to the program EWS [5] to run specific longterm simulations that consider the progressive degeneration of the borehole temperature.

Besides the building configuration, the two relevant components in the simulation with TRNSYS are the heat pump (HP), which is simulated with Type 668 and a borehole (GSHX), which is simulated with type 557a. The efficiency of the heat pump process, expressed by the real Carnot Efficiency \(\text{COP}_{\text{real}}\), is defined by the ideal coefficient of performance, \(\text{COP}_{\text{ideal}}\), and the Carnot Efficiency. The information used in the simulation is based on results from Wellig, Wyssen et al. [6] for a test facility of a chiller with low temperature lift, as shown in Figure 2.
Although the Carnot efficiency of approximately 55% for temperature lifts above 25K is above currently available products (which are about 45%), this machine represents the efficiency that commercially available heat pumps will potentially reach in the near future.

The GSHX is dimensioned according to the results of a pre-assessment with the software EWS that determines the minimal length by the norm SIA 384/6 for boreholes in Switzerland [7]. This standard requires that the minimal mean borehole fluid to be -1.5°C after 50 years. This dimension of the GSHX is also used in the simulation with TRNSYS. The hydronic loops of the TRNSYS model shown in Figure 3 allow for heating and cooling processes. The green color indicates the loop inside the building between the heat pump and the radiant floor heating. The loop marked in red indicates the exterior loop between the heat pump and the GSHX. The blue loop is optional. This loop is used for free cooling modes. The controls (FBH), limit the surface temperature of the floor radiant heating and the room temperature according to the standards of the SIA 2040. However, a hysteresis control allows for some deviation to reduce permanent on/off routines of the heat pump. Thus the room temperature can temporarily drop a little below 20°C during the coldest days of the year, but in general stay above this temperature. The controls determine the setting of the valves and the on/off mode of the pumps, including the heat pump.

Figure 2 Results from a test facility, by Wellig, Wyssen et al.
5. Results

Figure 4 shows the results of refurbishing the building with EPS and CWB insulation material in combination with a heat pump system powered by electricity from the standard Swiss electricity mix. The various possible insulation thicknesses (abscissa) affect the annual heating demand. This consequently determines the dimension of the ground source heat exchanger and the heat pump. The blue dashed graph illustrates the embodied GHG emissions due to the installation of the ground source heat exchanger (GSHX), the installation of the heat pump (HP), the installation of the radiant floor heating (RFH) and the dismantling of the existing radiators and the condensing boiler. The borehole is sized to the minimum required length based on the standard SIA for boreholes. The red dashed graph represents the direct GHG emissions due to the electricity demand, which is a result of the building operation. The solid grey graphs represent the embodied GHG emissions from to the insulation material EPS and CWB respectively.
The solid black graphs illustrate the total annual equivalent GHG emissions (GHG\textsubscript{e/a}) of each case. According to this assessment, the lowest total GHG\textsubscript{e/a} emission with CWB would require insulating the exterior walls with 41cm, which is beyond any reasonable refurbishment. The lowest total GHG\textsubscript{e/a} in combination with EPS is achieved with 15cm, but would generate more GHG\textsubscript{e/a} than insulating with CWB. Due to the very low gradient of the overall graph for CWB insulation, deviating from the optimal thickness has relatively low effect on the total GHG\textsubscript{e/a}. Choosing 15cm instead of the 41cm with CWB would still generated less than the minimal possible GHG\textsubscript{e/a} with EPS.

As already shown in Table 2, the specific emissions per purchased unit of electricity differ largely. The amount of GHG emissions from the purchased electricity is of less concern when insulating with thick layers of material, as a low heating demand also reduces the electricity demand, and consequently the differences of the sources become less significant. Figure 5 illustrates the effect that different electricity sources have on the total GHG\textsubscript{e/a}, when insulating with EPS material. The black graph matches the black graph in Figure 4. The red and green graphs show that the total GHG\textsubscript{e/a} when choosing different electricity mixes. Consequently, the lower the GHG\textsubscript{e/a} of the purchased electricity, the less insulation material is required to achieve the lowest GHG\textsubscript{e/a}. While the annual heating demand rises when reducing insulation thickness, the efficiency of the heating system increases. This is because of the necessity of installing deeper boreholes to provide the rising heating demand. Deeper boreholes, however, positively affect the COP of the heat pump process as deeper boreholes provide in general a higher return temperature, which reduce the temperature lift the heat pump needs to provide. However, this only compensates for some of the increased
electricity demand. A tipping point is reached, when the savings of the embodied GHG due to less installed insulation material cannot compensate the rising electricity demand. This is when the graphs rise sharply. The low gradient of the graph representing the total GHG\textsubscript{e/a} with “solar-top” allows great flexibility in terms of insulation thickness. The total GHG\textsubscript{e/a} does not significantly change in the range of 4cm to 24cm of insulation (less than 10%). Thus, the total GHG\textsubscript{e/a} emissions in this case are almost the same, whether the building is highly insulated with 24cm or minimally insulated with 4cm. One could also argue in an extreme case that not insulating the building in combination with purchasing the eco-power electricity mix is always better than insulating the building and purchasing the standard Swiss power mix.

![Minimal GHG\textsubscript{e,a} with EPS and electricity from different providers](image)

**Figure 5** Minimal GHG\textsubscript{e,a} with EPS and electricity from different providers

### 6. Discussion and conclusions

Most building regulations in countries of the temperate climate in Europe focus on the annual heating demand of a refurbishment strategy. This is reasonable, as long as the primary energy carrier is a fossil fuel. However, electrified buildings operating with heat pumps allow for two additional strategies to reduce the GHG emissions namely Combining high and low exergy in heating systems and Substituting the energy carrier or building materials.

Applying all three strategies we were able to show that the minimal total GHG\textsubscript{e/a} emissions in case of operating with electricity from the standard Swiss electricity mix, relatively reasonable thicknesses of 15cm insulation with the material EPS provide the lowest overall GHG emissions. It is worth noting that increasing the insulation thickness in this case to 20cm would
result in the same total GHG$_{e/a}$ emissions as reducing the insulation to 11cm. Choosing a different insulation material shifts the results, as shown with the CWB.

Substituting the primary energy source has considerable effect on the optimal balance of the active and passive building components. In case of purchasing electricity with very low specific emissions (here “eco-power”), it is more reasonable to insulate only 6cm of the EPS insulation material to generate the minimal total GHG$_{e/a}$ emissions. It is worth noting that even insulating the wall with minimal layers becomes a reasonable strategy. However, this depends technically on aspects if thermal comfort can be provided to the interior, which consequently depends on the available surface area and the load temperatures. Furthermore, demanding more primary energy from renewable sources also depends on the availability of such a source. As a result, the electricity demand would rise during the cold season. It is necessary to study the peak demands such a strategy.

Current regulations regarding energy saving in refurbishment projects request high thermal resistances of the building envelope. We found that this request can be counterproductive in terms of GHG emissions if the purchased power comes with relatively low emissions and the heat pump process is energy efficient. In this case installing more insulation beyond the optimal balance of active and passive components even increases the total GHG$_{e/a}$ emissions of that building. Thus, intending the lowest possible GHG$_{e/a}$ in a refurbishment project with a heat pump heating system combined with a GSHX can not be guaranteed by a normative approach, but requires an individual assessment as presented.

7. References


