Embodied and operational energy use of buildings

L.C.M. Itard¹
¹Research Institute OTB,
Delft University of Technology, Delft, the Netherlands

Abstract
Up to now energy savings in buildings have been approached from the side of their operational energy. However, when the operational energy use is reduced, the embodied energy use (i.e. the energy embodied in the manufacture and transport of building components) could become an important item. In this paper we present the results of an energy flow investigation, based on LCA considerations, on the relative values of embodied and operational energy of dwellings and dwelling renovation. The environmental effects resulting from energy use are addressed as well.

Keywords:
Life cycle assessment, embodied energy, materials, operational energy use, passive houses

1 INTRODUCTION
Energy savings in the built environment have a high priority on the politic and scientific agenda. Costs savings, security of supply and the environment are the main reasons to save energy. When the operational use for heating is reduced considerably, the energy embodied in the manufacture and transport of building components (embodied energy) could become an important item. In the past, there have been few studies of the embodied energy of conventional dwellings. The energy use of an Australian house has been analysed for a thirty-year life cycle in [1], where the relative importance of energy consumption with respect to the way the house is used and to household behaviour was stressed. The relative values of the embodied and operational energies were found to be an important factor in choosing design strategies, such as insulation ([2], [3]). In [4], the embodied energy in a refurbishment project is compared with the embodied energy for demolition and new construction. It was found that the demolition of buildings should be regarded as environmentally unfriendly. These papers provided an analysis that focused on energy use, but did not consider other environmental effects. Environmental effects were considered in [5], to compare three types of dwellings. The results were aggregated for the entire life cycle of the building. Some of the impacts that were used in [5] to determine the final environmental profile of the dwellings were interdependent (e.g. energy and global warming potential), possibly resulting in a distorted profile.

The present paper is based on the method developed in [6] and presents first the results of a research on the relative value of operational and embodied energy use for renovation measures and for energy efficient new built dwellings. Second, the paper elaborates on the fact that energy use in itself is not an environmental problem, but the cause of a number of environmental problems. The relationship between energy use and environmental impact is studied using a LCA (Life Cycle Assessment) approach.

2 EMBODIED AND OPERATIONAL ENERGY USE IN RENOVATION
The production of the building components that are needed when building or renovating a dwelling costs energy. This energy is needed to extract the raw materials, to transport them and to produce the components. The overall energy use of building activities can be quantified by using Life Cycle Assessment (LCA). EcoQuantum, version 2.00 ([7], [8]) was used. EcoQuantum is a Dutch LCA tool for assessing the environmental effects of buildings in terms of material use, energy consumption, water consumption and environmental impacts. EcoQuantum uses a particular Dutch database of building materials maintained by IVAM. The impact assessment method is based on the CML-2 method. The role of the EcoQuantum tool with respect to other international LCA tools was discussed in [9] and [10].

During a life cycle assessment the energy use, the type of energy and the environmental effects are mapped from cradle (raw materials extraction) to grave (disposal), according to [11]. This includes production process and operational energy and material use. The operational
energy use is defined as the energy needed to heat, cool and ventilate the dwelling and to power electrical appliances in the dwelling. In the present study, the operational energy use is limited to the energy use for heating and ventilating. Opposite to the operational energy use that can be calculated simply by using the U-values of the construction parts, the embodied primary energy use can only be calculated if the types and masses of materials used are known. The calculations in the present study were conducted for a terraced house, representative of houses built between 1966 and 1976 in the Netherlands ([12], [13]). The operational energy use of the dwelling was calculated using the EPA software [14]. The main characteristics of the dwelling before renovation are given in Table 1. To calculate the primary energy use related to electricity, the average efficiency of a Dutch electricity plant was used (0.39). The non-renovated dwelling is heated by a standard efficiency combination boiler. Auxiliary energy for pumps, ventilators and other HVAC equipment is taken into account, as well as the electrical energy needed to power the heat pump (in variant 4). The electricity use related to lighting and white and brown goods is not taken into account. Six renovation variants are studied.

**Variant 1**

In variant 1 the façades (including roofs and ground floor, but excluding windows) are insulated. The U-value of the façade is then 0.35 W/m²K, the U-value of the roof 0.31 W/m²K and the U-value of the ground floor is 0.34 W/m²K. For the facades and the roof stone wool insulation is used and finished by a coat of plaster. The ground floor is insulated with a Tonzon thermocushion (foldable insulation) with a Rc-value of 2.25 m²K/W.

<table>
<thead>
<tr>
<th>Useful floor area (m²)</th>
<th>139</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground floor</td>
<td></td>
</tr>
<tr>
<td>Surface area (m²)</td>
<td>56</td>
</tr>
<tr>
<td>U-value (W/m²K)</td>
<td>2.3</td>
</tr>
<tr>
<td>Roof</td>
<td></td>
</tr>
<tr>
<td>Surface area (m²)</td>
<td>66</td>
</tr>
<tr>
<td>U-value (W/m²K)</td>
<td>1.0</td>
</tr>
<tr>
<td>Facades (excl. windows)</td>
<td></td>
</tr>
<tr>
<td>Surface area (m²)</td>
<td>36.2</td>
</tr>
<tr>
<td>U-value (W/m²K)</td>
<td>1.8</td>
</tr>
<tr>
<td>Windows</td>
<td></td>
</tr>
<tr>
<td>Surface area (m²)</td>
<td>17</td>
</tr>
<tr>
<td>U-value (W/m²K)</td>
<td>5.1</td>
</tr>
<tr>
<td>Space heating &amp; hot tap water</td>
<td>Standard efficiency combination boiler</td>
</tr>
<tr>
<td>Ventilation</td>
<td>Natural</td>
</tr>
<tr>
<td>m³ gas/year for space heating</td>
<td>1242 (=39371 MJ primary energy)</td>
</tr>
<tr>
<td>m³ gas/year for hot tap water</td>
<td>506 (=16040 MJ primary energy)</td>
</tr>
<tr>
<td>kWh/year auxiliary energy</td>
<td>427 (= 3942 MJ primary energy)</td>
</tr>
<tr>
<td>MJ Total primary energy / year</td>
<td>59354</td>
</tr>
</tbody>
</table>

Table 1: Main characteristics of the reference dwelling

The principle of the calculations is shown in figure 1, per m² surface area of the dwelling: in year 0, the year of renovation, energy is used to produce and place the new building components (embodied energy). Therefore there is more initial energy use when the building is being renovated than when it is not. The operational energy use decreases after renovation. Figure 1 shows the cumulated values of the energy use all over the years. The slope of the lines includes the replacement of the components at the end of their service life (linearized value). It shows that the energy embodied in a combination boiler (123 MJ/m² surface area) or in a combination and heat pump boiler (156 MJ/m² surface area), or in a solar boiler (218 MJ/m² surface area) is clearly higher than the energy embodied in insulation materials (26 MJ/m² surface area). However,
the embodied energy use is paid back by the lower operational energy use in less than 5 years — in all cases. The shortest energy pay-back time is achieved by insulation measures (variants 1 and 2) and the longest by the heat pomp boiler (variant 4).

Figure 1: Cumulated embodied and operational energy use per square meter useful floor area over 10 years (upper graphic) and zoomed over 1 year (lower graphic).

Figure 2: Embodied and operational energy use after 30 years for the different variants.

3 EMBODIED AND OPERATIONAL ENERGY IN LOW ENERGY NEW-BUILT

For this part of the research, the Ecobuild dwellings were used. These dwellings are very low-energy test dwellings used by ECN [16]. Dwellings A, B and C were compared with a reference dwelling. Dwellings A, B and C are very well insulated and all have a comparable insulation level, but the materials and HVAC equipment used are different. The main characteristics of the buildings are shown in Table 2. The service life of the building was set at 75 years. The life spans of all components can be found in [16].

It appears from figure 3 that the cumulated operational energy use during the whole service life can be halved if building concepts B and C are used instead of A or the reference. However, the energy embodied in dwellings B and C is higher than in the reference dwelling. Dwelling C performs better than the reference dwelling after only 6 years. Dwelling B needs 15 years to perform better and dwelling A 25 years. The energy embodied in the reference dwelling represents about 15 years of operational energy. Comparable values were found for instance in [1]. The energy embodied in low-energy dwellings A, B and C represents 34, 61 and 43 years of their operational energy respectively. This clearly means that the further reduction of the environmental impacts of dwellings will necessitate the reduction of their embodied energy use, because the embodied energy use may be responsible for more than half the total energy use for heating and ventilating.
Environmental effects are measurable damages to the environment. The use of fossil fuels to produce energy is not an environmental effect, but a cause of a number of environmental damages. In LCA studies with EcoQuantum, nine environmental effects are addressed: abiotic depletion; global warming; ozone layer depletion; photochemical oxidation; acidification; eutrophication; humane toxicity; fresh water aquatic ecotoxicity and terrestrial ecotoxicity. In this section the concept of environmental pay-back time, which is not used for operational energy use for heating. In our opinion, the environmental optimization of materials is substantial, and after 30 years, still far from negligible. This way we are able to study the effect of the service life and to calculate environmental pay-back times.

4.1 Renovation

Figure 4 show examples of the cumulated values of the environmental effects abiotic depletion, global warming, ozone layer depletion and terrestrial ecotoxicity for the different renovation variants studied in chapter 2. The embodied environmental effect can be seen in year 0. The slope of the line represents the linearized environmental effect from operational energy and material use (replacements). Comparison of figure 4 with figure 1 (primary energy use) shows that the primary energy gives a good indication of abiotic depletion and to a lesser extent of global warming. It does not reflect correctly the trends of the other environmental effects. For abiotic depletion – as for the primary energy use, all variants perform better than the reference after very few years. This is also the case for global warming, with the exception of variant 4 (heat pump boiler) that performs always worse than the reference. For terrestrial ecotoxicity all variants relating to heating and ventilating equipment perform worse than the reference. The variants with insulation perform better than the reference. For ozone layer depletion, the results are miscellaneous.

The results for all environmental effects are shown in figure 5, in which the environmental effects caused by the embodied and operational energy and material use over 30 years are plotted. Because the different environmental effects are expressed in different units, they were normalized to 100% for the reference dwelling. Noticeable are the poor performances of variants 4 (heat pump boiler) and 6 (balanced ventilation), except for abiotic depletion and to a lesser extent for global warming and eutrophication. Also for the other variants the positive effect of the renovation measures appear to be lower than the primary energy use indicated. However, insulation measures (variants 1 and 2) lead clearly to less environmental effects than the other variants. Insulation and replacement of the conventional boiler by a high efficiency one result in less impact for all environmental effects.

Figure 6 shows the environmental effects resulting from the operational energy use only (embodied energy and materials are excluded). To make comparison with figure 5 possible, all environmental effects, including those of the reference, were normalized with respect to the 100% value in figure 5. Comparison between figure 5 and figure 6 shows that the operational energy use contributes for a very large part to the environmental effects abiotic depletion, global warming and eutrophication. The contribution of embodied energy and embodied materials is minimal for these effects, but they clearly play a much more important role in all other environmental effects. This means that the environmental optimization of materials used for heating and ventilating equipment is important, because their effect on ozone layer depletion, photochemical oxidation, acidification and all toxicity items is substantial, and after 30 years, still far from negligible. Particularly important seems the optimization of the solar
boiler, whose poor performance arises in large measure from material use (steel vessel).

However, most of environmental peaks in figures 5 and 6 come from the operational energy use. Variants 4 and 6 cause a particularly high worsening (up to more than 3 times the environmental effect of the reference) for six of the ten effects studied. This worsening is directly related to the increase of the electricity use in comparison with the reference. Electricity is used in variant 4 for the heat pump boiler and in variant 6 to power the ventilators for the balanced ventilation. The increase in environmental effect is caused by the switch from gas use to electricity use. Due to the actual Dutch average fuel mix for electricity production (30% oil, 5% coal, 50% gas, 10% nuclear and 5% renewables), a very limited change-over from gas demand to electricity demand causes a substantial increase of the environmental effects ozone layer depletion, photochemical oxidation, acidification, humane toxicity and ecotoxicity.
An unfair conclusion would be that heat pumps should not be used because they increase the environmental burden. The right conclusion is that heat pumps should not be used if they are powered by a conventional electricity plant. Conventional gas is likely to have reached its limits with the high efficiency boiler. By contrast, heat pumps can achieve a much higher efficiency and have a high improvement potential. The use of electricity produced by a more sustainable fuel mix, or better, renewable sources, is a requisite when applying heat pump technology.

4.2 New-built

Similar calculations were conducted for the Ecobuild dwellings (see section 3) and are presented in figure 7. The analysis leads to the same conclusions as for renovation.

5 CONCLUSIONS

This paper compared the primary operational energy use for heating of several renovation and new-built variants with the primary energy embodied in the variant itself. It was found that after 30 years of use, the embodied energy in renovation variants is very low, opposite to the embodied energy in "low-energy" new-built that can amount up to 60 years of operational energy use. This
means that the further reduction of the environmental impacts of dwellings will necessitate the reduction of their embodied energy use.

However, energy use is not an environmental effect, but the cause of several environmental damages. The paper demonstrated that the primary energy use renders reasonably abiotic depletion, global warming and eutrophication. For other environmental effects (ozone layer depletion, photochemical oxidation, acidification, humane toxicity and ecotoxicity) the primary energy use is not representative for the real environmental impact, especially when there is a shift from gas demand to electricity demand. That is the reason why heat pump boilers and balanced ventilation perform poorly. This cannot be solved without switching to sustainable electricity production. Insulation measures appear to be efficient for all environmental effects.

6 REFERENCES


[14] EPA, B-versie 4.02, in Dutch http://www.senternovem.nl/epadesk

[15] Levensduur van bouwproducten – praktijkwaarden; SBR; Rotterdam, 12/1998

Itard, intern rapport, OTB, www.otb.tudelft.nl, –in Dutch

